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DIVISION OF ENGINEERING AND WEAPONS

Report EW-10-00

# NAVY 44 SAIL TRAINING VESSEL DESIGN IMPROVEMENT PROJECTS

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ABSTRACT

Three midshipmen, through independent research credit courses and summer internship projects studied potential improvements to the Navy 44-foot sail training vessel. All three projects were initiated based on feedback from various user-groups. The first project studied stability and performance issues. Full-scale inclining and resistance tests were performed on a Navy 44 at the Academy. This data was used in a Velocity Prediction Program to predict potential design improvements. Results indicated a lower center of gravity (CG) keel, combined with a longer waterline and reduced displacement, would produce a safer design with improved performance. A new, low CG keel was designed. The second project studied stiffness, flexural strength and impact resistance of proposed hull laminates. Testing included 4-point flex coupons and two-foot-square impact panels. Results indicated a lighter, stronger, and less expensive laminate than the current laminate is possible. The third project developed a preliminary deck plan that addresses safety and crew-efficiency issues of the current design. The new plan improves safety while providing a more comfortable working environment.

During the spring and summer of 2000, three midshipmen participated in research and design projects addressing potential improvements to the current 44-foot sail training vessels used at the Naval Academy. Their reports are attached and this cover sheet serves to summarize their findings and put their results in perspective.

The three midshipmen's backgrounds are directly related to their topics. All three are naval architecture majors who participated on the offshore sailing team and are accomplished sailors. ENS DeMeyer graduated in May and will attend SWOS prior to reporting to a DDG. He is a recipient of the prestigious Engineering Duty Officer option and his topics included stability, resistance and performance issues. MIDN 1/C Arvidson has designed and built his own boat and chose to study construction options for the new 44's. MIDN 1/C Taylor is considered one of the best "bow persons" on the offshore team, has sailed as foredeck crew on numerous designs, and chose to study potential improvements to the deck and cockpit layouts. Their total effort on the three projects amounted to over 500 man-hours.

The current Navy 44 is a proven offshore sail training vessel with a good safety record. Its specifications were empirically developed over many decades and include lessons learned from previous Navy yawls. In shape and rig, it shares characteristics common to CCA and early IOR designs. Although a great design, numerous advances in materials, computer-modeling tools, and hardware have occurred since it was designed. Additionally, the field of yacht design has accumulated another 20 years of empirical experience with hull shapes and their effect on seaworthiness. The three midshipmen chose topics exploring these advances to determine possible design improvements. Design limitations included maintaining the same rig dimensions, length overall, maximum draft and maximum beam.

Keel Design and Performance Improvements: ENS A. DeMeyer

The current Navy 44 keel is a trapezoidal shape characterized by a relatively high center of gravity (CG) compared to more recent designs. Lower CG's produce greater stability. Nonetheless, the IMS limit of positive stability for the design is 129 degrees, higher than currently common, but lower than those of designs common from the 1920's to 1960's. Experience from the Fastnet, Sydney-Hobart and other storms indicates that for capsize safety, high ballast stability combined with a high roll mass moment of inertia and moderate displacement is desirable. This is best achieved by a low center of gravity keel. ENS DeMeyer designed a keel with a lower CG that increased stability, increased roll mass moment of inertia, increased roll damping and yet still met the stringent ABS grounding criteria. Due to the increased inertia and roll damping, the roll comfort should be equivalent to the current design. Two beneficial side-

effects were a reduction in keel weight, and with the help of a Boeing fluid dynamicist, increased keel efficiency.

With support from the Hydromechanics Lab and an advanced performance prediction program provided by an America's Cup consultant, ENS DeMeyer also explored how small design changes might improve performance. His recommendations to reduce the bow and stern overhangs, take advantage of keel and laminate weight savings and reduce canoe body depth all yielded significant performance improvements. Although performance is not a major criteria for the 44's, current complaints of significant motoring hours to meet schedules indicates more speed under sail is highly desirable. Not coincidentally, his proposals also indicate an improvement of roughly 0.5 knots for an equivalent THP at cruise. His "mid-line" proposal makes good sense. Copies of his inclining, keel design, resistance and VPP reports are attached.

Laminate Structural Analysis: MIDN 1/C M. Arvidson

The current 44's were built of vinyl ester resin, knitted E-glass and Airex core. These materials were considered "leading edge" at the time and are still among the most durable available. The particular vinyl ester however, is not commonly used now due to environmental concerns. With strong support from industry and the Academy's Structures Lab, Model Shop and SCRD, MIDN Arvidson performed extensive analysis and testing of currently available materials. Results from 4-point coupons, panel pressure tests, and bow impact tests showed that certain combinations will yield hull and deck laminates that are tougher, stiffer, lighter and less expensive (both in raw material and fabrication costs) than those in the current boat. His recommendations include using either a ProSet 117 resin infusion epoxy or Dow 8084 vinyl ester with knitted E-glass fabrics and CoreCell core. To improve properties over the current laminate, the new laminate should include as a minimum, two layers of 18 oz and one layer of 24 oz on each side of the core. The vinyl ester would also require a veil cloth.

Deck and Cockpit Layout: MIDN 1/C C. Taylor (interim report)

Beginning with interviews of sailors and evaluations of the Navy 44 and other craft's layouts, MIDN Taylor compiled a list of desireable and undesirable design features. Incorporating the desirable characteristics while meeting ORC and IMS regulations, MIDN Taylor developed a preliminary deck layout that increases crew efficiency on the foredeck, reduces equipment interference, improves comfort and removes two hazardous conditions. The new cockpit layout reduces crowding, improves visibility and communications, removes a hazardous condition, increases drainage, and improves man-overboard recovery. This project will continue through the fall semester on a time-available status and will become part of MIDN Taylor's capstone naval architecture design course in the spring.

Perspective

As with any good research and design effort the three projects generated numerous questions as well as answers. Their attached reports discuss many of both. Additionally, any good project is a learning experience for the researcher. This was clearly evident as they identified, tested and were able to dismiss many common misconceptions in sailboat design. Having helped them from start to finish, I am pleased that their final results are well researched, (mostly!) unbiased, and within the limitations of the facilities and time available, of significantly higher quality than typical for student projects. Based on my engineering background and experience participating in the design of over two-dozen sailing vessels, as well as over 5,000 hours of offshore sailing and over 6,000 hours of instructing sailors, I would not hesitate to recommend that the suggestions outlined above be adopted in the new design.

Dr. Paul H. Miller
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United States Naval Academy

31 August 2000

# Navy-44 Inclining Experiment (7 AUG 2000)
## Discussion and Results

ENS A.P. DeMeyer, USNR

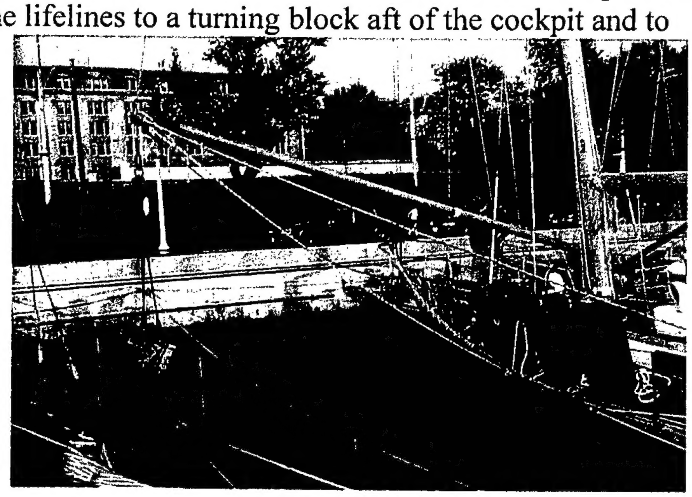
INTRODUCTION:

The Navy-44 incline experiment described in the following passages is a part of the ongoing study by the United States Naval Academy into possible improvements to the original McCurdy and Rhodes design of the Academy's 44-foot sloops. This study and others like it will ensure that the next generation of sloops used by midshipmen will surpass the already stellar safety record of the existing design as the current boats are replaced and retired from service. Specifically, this inclining experiment was conducted to obtain a fuller database of the existing design to be used in comparison with suggested improvements. Results of the experiment indicate that stability is reduced in the full-load condition.

SETUP:

NA-14 *Intrepid,* a McCurdy and Rhodes 44-foot sloop in the USNA sailing fleet, was used as the test model for this experiment. Scheduled for departure at 1200 that day, the boat was in the typical full-load condition for a CSNTS (Command, Seamanship and Navigation Training Squadron) cruise.

To facilitate the generation of heeling moment, the spinnaker pole of the boat was rigged to the spinnaker gooseneck and led outboard to where the outboard end of the pole was even with the upright LCF. The outboard end of the pole was held in place with the port jib halyard rigged to the downhaul eye of the pole. The port spinnaker halyard was then passed through the jaw of the pole at the outboard end to serve as the hoist for heeling weights. Both halyards were secured to winches on the deck of *Intrepid.* To hold the pole in place longitudinally, two guys were attached to the outboard end of the pole as well. The after guy led outside of the lifelines to a turning block aft of the cockpit and to the secondary winch in the cockpit. The fore guy was led to the mooring chock portside and aft to the starboard spinnaker winch. For additional weight, several locations on the deck were marked off with duct tape in order to place weight evenly and as near as possible to the LCF while allowing for the greatest possible heeling moment. Four 32-gallon trash cans were previously filled with fresh water and weighed.



In order to properly measure the heel angle of the boat, two digital inclinometers were obtained from the Hydromechanics Laboratory. They were set in position on horizontal Dorade covers roughly seven feet apart and secured with double stick tape. Finally, the recorder's position was marked off along the centerline of the vessel with a piece of small line.

PROCEDURE:

Before changing conditions on the boat (i.e. adding weight or changing the rigging configuration), an initial zero-heel measurement was taken from both inclinometers. Next, the spinnaker pole was rigged as described in the previous section of this report. A second measurement was taken from this initial condition to take into account the weight and moment of the pole. From there, four one-hundred pound weights were suspended by a suspension tackle of known weight from the spinnaker halyard, hoisted from the deck of a second Navy-44. Heel angles were measured after each of the blocks were added to the tackle. A fifth weight (50 lb.) was then suspended as well.

Additional moment was provided by placing the 32-gallon trash cans over the marked locations on the deck and filling them one at a time. Measurements were taken after each of the cans was filled to the previously marked location. Finally, two known weights (Prof. Paul Miller and Mr. John Zseleczki) stood over marked locations on the deck as additional heeling moment.

After collecting the data, an analysis spreadsheet was generated in Microsoft Excel. Data collected during the experiment was analyzed using linear regression to produce a righting moment curve for small angles (up to eight degrees) and a GM calculation. Data from the offset drawings was then used to find the KG location for the full-load sloop for comparison to data generated for IMS ratings certification in the half-load condition for a similar boat.

DISCUSSION:

Inclining experiments are used principally to calculate the GM (metacentric height) and KG (vertical center of gravity above the baseline) of vessels in various conditions. They can also be used to generate low-angle righting moment and GZ curves. All of these are indicators of stability (particularly GM) and are useful for comparison between similar designs with respect to seakeeping properties. Of particular interest in this experiment, the boat was heeled in the full-load condition (no fuel jugs), making it possible to compare IMS stability calculations to calculations for the existing boat *as it is actually used to sail.* CSNTS, one of two primary offshore sailing programs for the boat, standardizes the loading of the fleet prior to getting underway, making this study useful for determining what effect, if any, the loading of the vessel has on stability.

The minimum recommended stability index mandated by the Offshore Racing Council for Category 1-Offshore Races is 115 degrees. This corresponds to a Limit of Positive Stability (LPS) of approximately 110 degrees. The McCurdy and Rhodes Navy 44 design exceeds this value at an LPS of 129. There is no "magic LPS value" however, and greater stability translates to increased capsize resistance.

A reduction in initial stability is expected for a full-load boat when compared to the half-load. This is because the KG value for the boat is generally expected to rise, in turn reducing both the righting moment and the GM for the vessel. It is interesting and important to note that for such a heavy boat, the addition of relatively small amounts of weight causes measurable differences in initial stability.

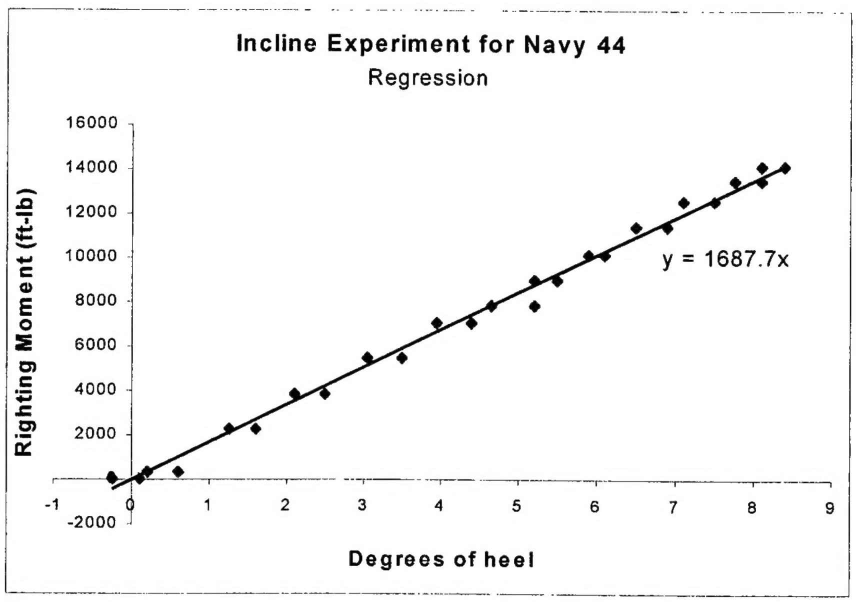
COMMENTS AND SUGGESTIONS FOR FURTHER STUDY:

The spinnaker pole and suspended weight setup was perhaps the most useful way to heel the boat in the given conditions. Future tests would be best conducted using a similar method. It is both quicker and more accurate for measurement purposes.

It cannot be stressed enough that the water in the test area must be kept as calm as possible. Measurement of heel angles can be difficult when wake from boats in the nearby river or in the basin itself cause the boat to rock. In addition, hanging 450 pounds from the spinnaker halyard at the end of the pole tends to make the pole want to sky if it is rocked, and the platform the weights are hoisted from (in this case, another 44) is in danger of being hit by the weights. The first of these problems can be solved in part by tying a down haul to the pole (though this means a *lot* of gear at the end of the pole), but the second problem can only be solved by using a different platform, such as a RHIB or Whaler, which can get out of the way easily. That option is less than optimal, however, as the boats would require more hands to conduct the experiment.

CONCLUSIONS:

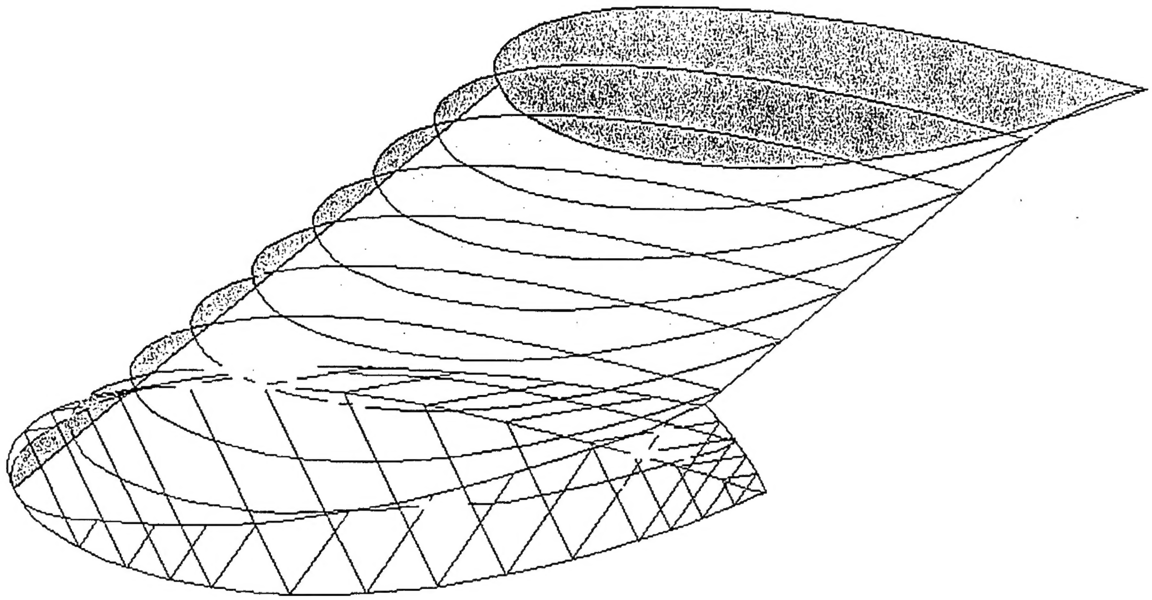
The data gathered in the experiment agreed with predictions. IMS half-load incline righting moment for low angles was given as 1815.6 ft-lb/deg. The inclining experiment conducted in Santee Basin at the full-load condition revealed a righting moment of 1794.5 ft-lb/deg, about 1.2% lower.




| | |
|---|---|
| **Regression RM coefficient:** | 1687.7 |
| **Adjustment factor for added weight:** | 1.063 |
| **Corrected RM coefficient:** | 1794.516 |

As the regression graph indicates, there was little scatter in the data. This was in part due to the redundancy in measuring devices and in part due to the calm waters in the basin. The linear nature of the graph agrees with the expected shape as well, and the righting moment per degree generated by the slope of the graph is similar to that listed in the IMS certification, giving further credence to both pieces of information.

Two possible improvements to the current design immediately present themselves as a result of this experiment. Both involve either weight reduction, weight re-location, or both. First, a lighter mast and lighter rigging could lower the KG of the boat, increasing stability. Removing excess gear and hardware from the deck, as well as increasing tankage so that deck-mounted jerry jugs are not needed, would produce similar results. The second option is to re-configure the keel shape. By adding a bulb or adjusting the configuration of the keel, the keel's center of gravity (and hence the center of gravity of the boat) can be lowered as well. Neither of these options is particularly difficult from an engineering perspective, and there are several potential benefits to both changes in sailing performance. Essentially, the way to improve the current design is to remove topside weight while simultaneously shifting weight lower (below the current KG).



# USNA 44-Foot Sloop Keel Re-Design Project


MIDN 1/C A.P. DeMeyer
EN 496
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08 MAY 2000

# USNA 44-Foot Sloop
# Keel Re-Design

MIDN 1/C Aaron P. DeMeyer

## ABSTRACT

The Naval Academy 44-Foot Sloop is a robust, proven design which has been in operation since the mid 1980's. The sloops are used for offshore sail training, P-100 (basic seamanship), major offshore regattas, and even as parade backdrops during the drill season. As the sloops near the end of their service lives, a study is underway aimed at improving on the existing design by making it more maneuverable, faster, safer, and more ergonomic than it is today. The new Navy 44's will hopefully then carry on the fine sailing tradition of her older sisters.

Part of this intensive study is the development of a newer, more innovative keel design. As nearly half the displacement of the vessel, the ballast keel on the Navy 44 deserves a close inspection. Several aspects of the design may warrant improvement. First, the current keel has a geometric aspect ratio of only 0.47. In addition, the current center of gravity is relatively high, in turn limiting the righting moment and the range of stability. Finally, the section shape used in the current keel is based on research from the 1940's. Present-day research has revealed newer, more streamlined foil shapes for use in keels.

The new Navy 44 keel, therefore, will take these flaws into account. An attempt has been made to increase the aspect ratio, decrease planform area, decrease the ballast weight, lower the center of gravity, and increase the righting moment. In addition, the new keel is still required to meet applicable rules and maintain or decrease the original draft of the vessel.

To solve these problems, a generic spreadsheet was developed to analyze the Navy 44-keel for performance data. The same spreadsheet was then applied to several concept designs in an effort to improve the overall performance of the Navy 44 keel. The results were astounding. Target weight reductions were reached and exceeded, as were goals for increased righting moment. Lift/drag properties were improved as well, and the planform area of the keel was reduced. The center of gravity also dropped significantly. Finally, the new keel is designed for ease of construction. The hull/keel attachment is flush and simple, with 18 through bolts molded into the lead ballast keel. Also, due to the shape of the keel, only a single mold is required for construction, saving on initial costs even above the material savings.

The keel re-design is a work in progress. Several aspects of the design could use another look, and as yet, no model data is available. Further study and testing this summer will refine the new concept and ensure it is viable as a replacement to the current system. Promising results warrant this effort.

USNA 44-Foot Sloop Keel
Re-Design Project

The McCurdy and Rhodes Navy 44 is a solid platform, which has served midshipmen afloat on Command Seamanship Navigation Training Squadron (CSNTS), and Varsity Offshore Sailing Team (VOST) cruises for nearly twenty years. The design, a robust cruiser/racer, is meant to take a crew of ten on short (i.e. approximately five to seven day) ocean passages, yet be both safe and simple enough for training inexperienced crews and fast enough to be competitive in offshore racing and big boat buoy races. To date, the boats have performed their roles very well. The 44 has an impeccable safety record, and she is still in use in major fleet racing on the Chesapeake Bay and in summer racing programs along the East Coast. CSNTS is in full swing as well, training midshipmen in basic seamanship.

What the Navy 44 offers that other vessels cannot is a large degree of sea kindliness for a boat her size. This is in large part due to her weight (27000 pounds). This aspect of the design has also been criticized, however, and an effort is underway to maintain or improve the sea kindliness of the vessel while simultaneously reducing the displacement, thereby increasing the speed of the boat. As the boats near the end of their service lives, a major study has been launched to confront this issue, as well as other issues regarding the hull shape, rigging, deck layout, and other features of the design. One aspect of this study involves the ballast keel. A more modern, slightly innovative keel design, utilizing an IMS bulb, a more aerodynamic shape, and constructed partially with composite materials will improve the performance of the Navy 44-foot Sloop.

To understand the concepts involved in changing the design of a keel, a fundamental understanding of keel design is necessary. As much art as engineering, keel

design requires patience, skill, and not a little bit of experience. In fact, few changes have been made in keel construction standards since the construction of the first Navy 44. A firm grasp of the concepts, however, will help build the experience base of the designer. As a guide, therefore, the basics of keel design and criteria must be covered.

Perhaps the first thing that comes to mind when thinking about a keel is that it is heavy. For the most part, this is true, as is certainly the case in the Navy 44. Any keel designed to place a significant portion of the vessel's weight at or near the baseline is called a ballast keel. Usually, these keels are constructed of lead and take up a large portion of the boat's displacement. In the case of the Navy 44, the keel accounts for 12,310 pounds of the total displacement. Essentially, the keel is half the weight of the boat! The purpose of the ballast keel is to improve the righting moment and mass moment of inertia for the vessel, meaning both slower rolling motion and a greater range of stability in a seaway (Killing p.97).

Secondary purposes of keels include keel lift properties and directional stability. While moving through the water, keels generate lift, increasing heel and effectively reducing the displacement of the vessel (at least in part) (Killing p.65). In addition, as a foil section flowing through the water, the heading of the keel is very nearly the boat's direction of motion. Keels, therefore, are a great benefit to the directional stability of the boat (Killing p.63). A very good example of this effect comes from the 12-metre boat design evolution for America's Cup racing. As keel designs went through further refinement, they became smaller and smaller. Helmsmen began to complain that the newer 12-metre yachts were very difficult to steer, as the bow of the vessels would swing

as much as ten degrees off course. Significant advantages in resistance and righting moment offset the effect, though it was a very noticeable concern (Marchaj p.44).

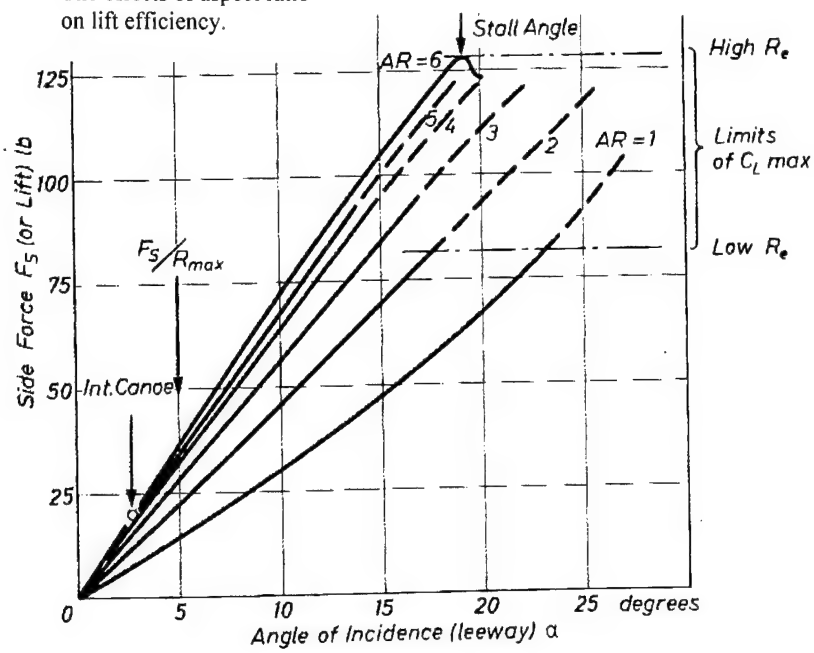
Along with the advantages of keels also come disadvantages. More specifically, the resistance and draft properties of sailboats depend in large part on the type and size of keels employed on them. Keels by nature increase the wetted surface of the vessel. Effective keels, moreover, tend to have large surface areas, in turn increasing resistance. The trick, therefore, is to design a keel that limits resistance for a given surface area. The obvious solution is to design the keel the same way one would design a wing. Indeed, the typical keel section is an airfoil section (Eliasson/Larsson p.102). As any good aeronautical engineer would argue, the aspect ratio of the wing has a large effect on the wing's effectiveness. Aspect ratio is a ratio of chord length to keel draft, and can be calculated in several ways. For the purposes of this study, the following equation defines the geometric aspect ratio:

$$AR = \frac{\overline{C}}{T}$$

where Cbar is the average chord length and T is the keel draft from the baseline to the keel root. Most keels are designed to maximize aspect ratio (Killing p.67). This increases draft, however, which in turn limits maneuverability. The Navy 44 has a draft of seven feet, three inches. Any attempt to deepen the keel would also increase the draft of the boat. Fortunately, however, simply lengthening the keel is not the only way to increase the aspect ratio. Shortening chord lengths will generate a reduction in lift (due to reduced area) for a foil with an infinite aspect ratio, but as these chord lengths are decreased, the tip vortex generated at the baseline of the keel will also be reduced, adding more effective area to the bottom of the keel and in turn increasing lift (Eliasson/Larsson p.102).

The previous paragraph provides a discussion of the geometric aspect ratio. This is a simple gauge for comparison between keels, but in itself is not particularly useful. More important to design is the effective aspect ratio. As the keel root (the hull-keel intersection) meets the canoe body of the hull at nearly right angles, the hull acts as an end cap to the keel, allowing the keel lift properties to respond as if the keel were roughly twice as deep (Killing pp.68-69). For the purposes of this study, therefore, the effective aspect ratio is assumed to be twice the geometric aspect ratio of the keel. Figure 1 illustrates the magnitude of effect aspect ratio has on lift properties. Note the 10-degree leeway angle. Following the graph from the x-axis upward, an enormous change in lift can be seen between various aspect ratios for the same keel section. For an aspect ratio of six, the lift force is nearly three times that of the keel with aspect ratio of one (Marchaj p.42).

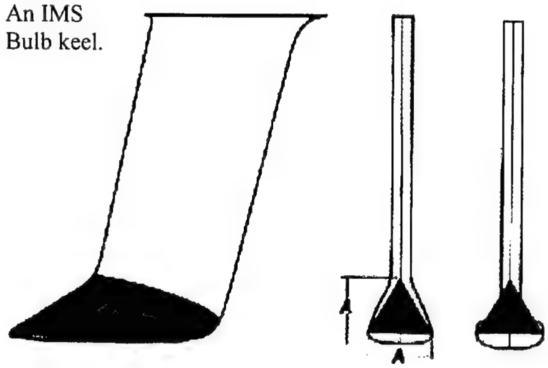
**Fig. 1**
The effects of aspect ratio on lift efficiency.




Another common attribute found in modern keels is a bulb. For this study, a keel bulb is essentially any object designed to add weight to the bottom of the keel in order to improve righting moment and mass moment of inertia. Several types of bulbs have been developed, but IMS (International Measurement System) rules do not allow for most of

them without paying a ratings penalty. The rules state that the thickness of any bulb or appendage at the bottom of the keel must be equal to or smaller than the height of the appendage. Imagine an isosceles triangle with the same height as base width. If the base of the triangle coincides with the greatest width of the bulb at any given section, the triangle would need to fit within the section shape of the bulb in order to meet the IMS rule. Figure 2 graphically depicts this requirement. The bulb on the left fits the IMS bulb requirements, while the t-shaped bulb on the right does not (Killing p.78).

**Fig. 2**
An IMS Bulb keel.




Keel profile is another essential aspect of keel design. Several shapes of keel are common, and most are designed to suit the particular needs of the vessel. For example, a slow-moving coastal cruising boat will likely have what is known as a restricted draft keel. This extremely low aspect ratio keel may run the length of the submerged hull form and be only a foot or two deep, designed to add ballast yet maintain the draft constraints of the vessel. A racing yacht of the same length may have a fin keel with an elliptical bulb, considerably lighter, deeper, and with a much higher aspect ratio. Another boat of similar size might carry an elliptical keel, while still another might have a keel centerboard attachment for use with a shallow draft keel (Eliasson/Larsson pp.113-115).

The current Navy 44 utilizes one of the more common of these keel shapes. With a fairly low aspect ratio (the geometric aspect ratio is 0.47), constant section shape, and gradual leading edge slope, the 44 Keel fits the definition of the plain deep keel. The chosen section shape for the current keel is based on research conducted on wing sections

by Abbott and von Doenhoff in the 1940's. The NACA 0012-34 section used in the keel is among the more common foil sections used in keel and hydrofoil construction today (Abbott/von Doenhoff pp.113-118). Though still commonly built, significant developments in section shapes have been made. The keel shape, weight placement, and aspect ratio combine to cause the boat to have trouble accelerating and may contribute to the boat's tendency to roll in heavy weather.

The current keel is a solid lead design. It is attached by 9 bolts to a short, oddly-shaped keel stubby. It's 12,310 pounds are therefore distributed fairly evenly, giving the keel a center of gravity approximately 27.5 inches below the keel root. For a keel this heavy, weight placement is crucial, as it affects the righting moment and mass moment of inertia of the keel. Also, the nearly rectangular shape of the keel makes for a fairly large planform area, adding viscous drag to the hull. The low aspect ratio of the keel also contributes to a loss of lift. Though the keel uses an efficient section shape, it is just too short to have efficient lift effects (See the attached appendix for a line-by-line keel comparison including the original keel analysis).

The proposed new keel design addresses these issues. First and foremost, the keel is designed to be significantly lighter. Still solid lead with a keel stubby, the new keel design incorporates less volume, resulting in about 2000 pounds less displacement. The shape of the keel was changed as well, utilizing a more streamlined section shape and shorter chord lengths. As a result, the aspect ratio of the new keel is much better than that of the original, improving lift and reducing drag. Another aspect of the new keel contributing to increased performance is the IMS bulb. The bulb distributes much of the weight of the new keel lower. This drives the keel's center of gravity below the original

keel's CG, even after taking into account the proposed decrease in draft of the canoe body. These changes result in an increase in righting moment and an increase in mass moment of inertia, both of which are a benefit to the current Navy 44 design.

The reduced weight benefits the keel in several ways. First, the reduction in raw materials usage reduces the cost of construction. Second, the lighter keel will make the boat itself lighter, allowing for quicker acceleration in light winds. Similarly, if the boat were to become involved in a collision with another boat (especially another heavy boat like a 44), to prevent serious damage, the boat should be as light as possible for given strength. The greater momentum of a heavier boat would likely cause greater damage to the side of another boat in a major collision, whereas the light boat would be more likely to bounce off or simply stop dead in the water.

With the aspects of keel design discussed in this study, a good qualitative analysis is easy to come by. Quantifying the changes to a keel design, however, can be a much different matter. In order to do so, a common means of measuring performance mathematically must be developed. To facilitate this process, and to make further research simpler, a spreadsheet has been developed which analyses a keel for various criteria. Several aspects of the keel are analyzed, including drag, lift, mass moment, weight, volume, planform area, area moment, and righting moment. In addition, the spreadsheet will calculate criteria regarding keel attachments. A thorough understanding of this important tool is fundamental to understanding the proposed new Navy 44 keel.

The keel analysis spreadsheet consists of 13 worksheets written in Microsoft Excel format. Navigating the spreadsheet is fairly simple, as each of the worksheets is labeled with the major function of the sheet. For example, nine of the sheets are labeled

"Station [x]," where x is a number counting sequentially from 1 to 9. The stations are horizontal "slices" separated evenly along the height of the keel. In this sense, the spreadsheet parallels traditional spreadsheets in the analysis of hull forms, in which an odd number of divisions are made evenly along the length of the long axis. This facilitates numerical integration using Simpson's Rule.

The first worksheet in the spreadsheet is labeled "Section_Shapes." This worksheet is simply a data storage page, in which four common section shapes are stored as non-dimensional offsets based on percentage of chord length. This handy page allows offsets to be called on in later worksheets. In addition, the Cl and Cd characteristics of these common shapes is also provided, based on a 12% thickness to chord length ratio. The final element of this worksheet is an aspect ratio correlation table. Based Figure 1, this table is used to compute an estimate of the actual lift generated by the keel rather than the "ideal" lift for an infinite aspect ratio (the data provided in most literature only includes infinite aspect ratio calculations and may result in inadequate designs).

All of this data comes in very handy when used in the following nine worksheets. The Station analysis pages are divided for ease of navigation and for clarity while "creating" a keel. Four inputs are required in order to generate a section: location of the leading edge, location of the trailing edge, maximum thickness, and location of the maximum thickness. The spreadsheet will then choose a section shape which best fits the provided data. A generalized section shape is provided (not to scale), and some preliminary data are available on the page as well. A thickness to chord length ratio is useful for ensuring that the section is not grossly different from neighboring sections.

Similarly, the area of the section is provided for comparison, in addition to the lift and drag properties of the section, properly scaled for the t/c ratio. The worksheet for Section 1 requires a fifth input. Labeled "Vertical Position," this input determines the height of the keel from the baseline to the keel root. It is also crucial in later calculations, as this input controls the vertical spacing of sections and has a large impact on later calculations.

Immediately following the Station[x] worksheets is the "Bulb" worksheet. This part of the spreadsheet also relies on four basic inputs. The format of the worksheet is similar in most respects to the section worksheets, but it includes other aspects as well. Inputting the thickness, location of max thickness, leading and trailing edge positions generates the baseline of the keel. The page then analyzes the baseline and generates a triangular "blister" to the keel, which the spreadsheet assumes continues to the baseline. The bulb is analyzed fore-and-aft for accuracy and divided into an odd number of stations for ease of numerical integration. The rest of the page is dedicated to these calculations, and a gray box displays pertinent information regarding the keel volume, weight, and centroid.

The next worksheet on the spreadsheet is the "First_Analysis" worksheet. This sheet has no inputs, but performs most of the major calculations involved in the spreadsheet. Calling on almost every other worksheet, this one correlates data in order to calculate the center of mass, aspect ratio, planform area, center of pressure, and volume of the keel. In addition, much of the initial calculations are performed for the analysis of the mass moment of inertia, righting moment, area moment, weight, and other values. Finally, this page calculates the lift force generated by the keel, as well as the total drag.

The final worksheet in the spreadsheet is a line-by line comparison of some of the more important values used in judging the performance characteristics of the keels. Here, planform area, weight, keel CG, mass moment of inertia (about the KG), area moment if inertia (also about KG), righting moment, drag and lift are displayed for the new keel in a blue box on the right hand side. The box on the left side contains information about the current Navy 44 keel. In the lift portion on the right side, rather than simply showing that more lift is generated at two degrees of leeway, calculates the theoretical leeway angle for equivalent lift. This is useful in explaining the way the vessel will turn, and also how well the boat will point. Typically, a sailboat has about between a two-degree and five-degree leeway angle upwind. If more lift can be generated for two degrees of leeway, however, the leeway angle decreases. As leeway can be described as the difference in direction between where the boat is headed and where it is pointed, this change can be significant, and any improvement is welcome.

In addition to the line-by-line comparison, the final worksheet also analyzes the keel bolt plan. It assumes that the material selected for the bolts is solid bronze, coarse thread. This is because analysis of materials concluded that the bronze was less prone to pitting corrosion, yet still has most of the tensile strength of stainless steel. A simple analysis is conducted to ensure that the bolt plan is adequate in both bending and in sheer. It is significant to note here that the spreadsheet never considers the hull composite and strength, though the new keel design assumes that the keel root itself is actually a part of the hull. This aspect is currently under review in another study, however, and should not be a major factor in the keel design.

The basics of the keel analysis spreadsheet reveal that it is indeed a complicated piece of work. A more thorough analysis of some aspects, however, reveals that the worksheets only make simpler work out of repetitious and tedious calculations. The mathematics can be difficult to follow when looking at the code inputted into the cells of the spreadsheet, so a brief explanation of some of the calculations may help explain the utility of this tool.

Probably the most often-used functions used in the spreadsheet involve numerical integration. Simpson's Rule and the Trapezoidal Rule are used extensively in the spreadsheet. Simpson's Rule, which in its simplest form fits a quadratic curve to three points in space and calculates an estimated area beneath the curve, is used to calculate the volume, weight, section areas, and is an aspect in most of the moment calculations, as well as the lift and drag calculations. Because the sections in many keels are not exactly alike, Simpson's Rule was not able to be applied directly to the lift and drag components of the spreadsheet, however. Lift is a function of planform area, which can only be calculated numerically in terms of station spacing. As the lift and drag properties at each section are not necessarily considered constant, numerical interpolation was used to infer an average value. This dropped the number of usable data points from nine to eight, however, necessitating the use of the Trapezoidal Rule in lift and drag calculations. Since these changes are generally gradual for a keel, however, this seemed a natural and very viable solution to a difficult problem.

Along similar lines, lift and drag were calculated based on well-established but tedious equations. Lift and drag can be found using the following equation:

$$L[D] = 1/2 \rho A v^2 CL[D] \text{ (PNA vol. II)}$$

This equation was applied to the spreadsheet directly by summing up the trapezoidal areas multiplied by interpolated CL and CD values. The calculations were all for a uniform velocity of six knots, which is a reasonable speed for a Navy 44.

Another important set of equations was used for the moment calculations. Crucial to comparisons between keels from a seakeeping standpoint, these equations are actually relatively simple, though. Righting moment is calculated with a simple statics equation and is simply weight multiplied by distance. The spreadsheet added pieces of volume from the "First_Analysis" worksheet multiplied by a calculated distance from KG. The sum of these values was the righting moment of the keel about KG. Mass moment of inertia was calculated in the same manner, but the distance from KG was squared. Area moment of inertia was also calculated in a similar manner, except that the areas were interpolated from chord lengths, and the final value was not summed using Simpson's Rule, but instead used the Trapezoidal Rule.

The keel bolt analysis equation is another important equation used in the spreadsheet. To calculate load for each keel bolt, the following equation was used:

$$\frac{8D\Delta}{2wN}$$

where D is the ballast depth (distance from KG to keel CG), $\Delta$ is the weight of the keel, w is the maximum distance between a keel bolt and the opposite side of the keel at the keel root, and N is the number of keel bolts used in the keel. This gave a safety factor of eight to the equation, ensuring that the values for bolt attachments would be well within the ABS requirements. The bending equation drove the size of the keel bolts to the point that the sheer equation was little more than a reality check. It was certainly not a limiting factor in the design (Gerr p.56-57).

By far the most interesting of the calculations in the spreadsheet involve the keel bulb. Rather than analyze the bulb as a separate entity, the spreadsheet assumes that the keel juts through the bulb and that the bulb is constructed around the keel. The gray box includes values for "Added Volume" and "Added Weight." These are calculated essentially as the difference between the weight of the keel part below the start of the bulb and the weight of the general section shape analyzed for the keel alone (without a bulb). In order to work properly, the bulb was analyzed in the opposite direction from the rest of the keel. To meet IMS requirements, the height of the bulb was set at 1.25 times the width of the keel base at every point along the length of the bulb. This made for a 25% safety margin in construction and allowed more weight low on the keel.

For each section of the bulb longitudinally along the keel, the vertical location of the intersection between the bulb and keel was calculated by finding the intersection between lines defined by the slopes of the keel and bulb at the location indicated. In places where the bulb jutted out beyond the trailing edge of the keel, the bulb height was simply 2.5 times the half-breadth of the bulb base width at that location. Added volume and weight were then calculated by summing the areas of the triangles formed by the thickness of the bulb base at each point minus the thickness of the keel at the keel intersection multiplied by the height of the bulb up to the bulb-keel intersect point.

With this format, the keel analysis spreadsheet is a valuable tool. With a relatively small set of input parameters, the keel is analyzed in short order, eliminating many questions relative to the type of keel and keel attributes in the design. In addition, the quantitative analysis of the keel is easy to read, and the line-by line comparison makes sense. Use of the spreadsheet requires only knowledge of which values need input, and

most of the spreadsheet cannot be altered without the proper code. Accidentally erasing a crucial cell, therefore, would be a difficult task.

As was previously stated, the keel analysis spreadsheet is a very useful tool. It is not, however, the only needed element in designing a keel. The numbers provided for the keel design must be then analyzed and compared to expected values, then a determination must be made as to the viability of the design. For example, the proposed new keel design has a larger righting moment than the one originally expected. The goal had been to produce a 20% improvement in righting moment about the KG. The proposed design actually has a 15% improvement. This means that the boat will probably have a shorter roll period, which may make the ride control characteristics slightly less comfortable. On the other hand, the lighter weight and great increase in the mass moment of inertia usually would mean that the oscillations would be both slower and lower in magnitude. The combined effect, therefore, is likely to make a more comfortable ride than the original keel allows.

One effect beyond the scope of this study is dynamic (quasi-static) roll stability. The equation for this is:

$$\Delta_S \int GZ d\phi$$

As the displacement has reduced by approximately 10%, and the initial righting moment GZ has increased by 15%, the net result should be little change. The actual values should be checked once the proposed hull lines are developed.

In general, keel design comes down to a short list of factors. Weight, weight placement, keel planform, section shape, and aspect ratio play crucial roles in the design of keels from a performance aspect. Low center of gravity allows for a lighter keel with a

good righting moment and mass moment of inertia. A proper section shape allows for a minimization of surface area for a given amount of required lift. A high aspect ratio utilizes the greatest proportion of the keel for the generation of lift, and generally increases the lift/drag ratio. Keel shape can also play a role in fouling prevention, and can be very important in determining the cost of the vessel. The simpler the shape of the keel, in other words, the cheaper the boat becomes.

These aspects of keel design are reflected in the re-design of the Navy 44 keel. The proposed new keel has a lower center of gravity, lighter weight, higher mass moment of inertia, higher righting arm, higher aspect ratio, and better lift/drag characteristics. The streamlined shape is simple and fouling resistant, easy to construct, and very likely cheaper to build than the current Navy 44 keel. The new keel's performance characteristics indicate a better ride, better point, and greater acceleration, Damage from collision is likely to be lighter due to the retention of strength but lower displacement (hence lower momentum) of the vessel. In short, the proposed new keel for the boat is a good design, deserving consideration as the primary keel for the New Navy 44.

## Sources:

1) 1994 American Bureau of Shipping Guide for Offshore Racing Yachts; American Bureau of Shipping; 1994.

2) Abbott, Ira and von Doenhoff, Albert; Theory of Wing Sections; Dover Publications; New York; NY; 1949.

3) Eliasson, Rolf and Larsson, Lars; Principles of Yacht Design; The Bath Press; London, England; 1994.

4) Gerr, Dave; The Elements of Boat Strength; International Marine; Camden, ME; 2000.

5) Killing, Steve and Hunter, Douglas; Yacht Design Explained: A Sailor's Guide to the Principles and Practice of Design; W.W. Norton & Company, Inc.; New York, NY; 1998.

6) Jones, Robert; Wing Theory; Princeton University Press; Princeton, NJ; 1990.

7) Marchaj, C.A.; Aero-Hydrodynamics of Sailing : Revised and Expanded Edition; International Marine; Camden, ME; 1979.

| NACA 4-digit | | NACA 001x-64 | | J 5012 series | | NACA 001x-34 | | |
|---|---|---|---|---|---|---|---|---|
| x | y(x) | x | y(x) | x | y(x) | x | y(x) | |
| 0 | 0.000 | 0 | 0.000 | 0 | 0.000 | 0 | 0.000 | |
| 5 | 0.036 | 5 | 0.033 | 5 | 0.033 | 5 | 0.025 | |
| 10 | 0.047 | 10 | 0.042 | 10 | 0.044 | 10 | 0.037 | |
| 15 | 0.053 | 15 | 0.049 | 15 | 0.051 | 15 | 0.045 | |
| 20 | 0.057 | 20 | 0.053 | 20 | 0.056 | 20 | 0.051 | |
| 30 | 0.060 | 30 | 0.058 | 30 | 0.060 | 30 | 0.058 | |
| 40 | 0.058 | 40 | 0.060 | 40 | 0.059 | 40 | 0.060 | |
| 50 | 0.053 | 50 | 0.058 | 50 | 0.055 | 50 | 0.058 | |
| 60 | 0.046 | 60 | 0.053 | 60 | 0.048 | 60 | 0.053 | |
| 70 | 0.037 | 70 | 0.045 | 70 | 0.039 | 70 | 0.045 | |
| 80 | 0.026 | 80 | 0.033 | 80 | 0.028 | 80 | 0.033 | |
| 85 | 0.021 | 85 | 0.025 | 85 | 0.022 | 85 | 0.025 | |
| 90 | 0.014 | 90 | 0.019 | 90 | 0.015 | 90 | 0.019 | |
| 95 | 0.008 | 95 | 0.010 | 95 | 0.008 | 95 | 0.010 | |
| 100 | 0.001 | 100 | 0.001 | 100 | 0.000 | 100 | 0.001 | |
| **Cl** | 0.0000 | **Cl** | 0.0000 | **Cl** | 0.0000 | **Cl** | 0.0000 | 0 deg. Leeway |
| **Cd** | 0.0098 | **Cd** | 0.0099 | **Cd** | 0.0058 | **Cd** | 0.0095 | |
| **Cl** | 0.2000 | **Cl** | 0.2000 | **Cl** | 0.2000 | **Cl** | 0.2000 | 2 deg. Leeway |
| **Cd** | 0.0103 | **Cd** | 0.0101 | **Cd** | 0.0065 | **Cd** | 0.0096 | |
| **Cl** | 0.4100 | **Cl** | 0.4100 | **Cl** | 0.4100 | **Cl** | 0.4100 | 4 deg. Leeway |
| **Cd** | 0.0116 | **Cd** | 0.0110 | **Cd** | 0.0081 | **Cd** | 0.0102 | |

**Values based on 12% sections

**Aspect Ratio Effects:** (AR= effective aspect ratio)

| AR= | % Effective lift |
|---|---|
| 1 | 29 |
| 2 | 42 |
| 3 | 52 |
| 4 | 59 |
| 5 | 63.5 |
| 6 | 67 |

# USNA 44-Foot Sloop Keel Re-Design

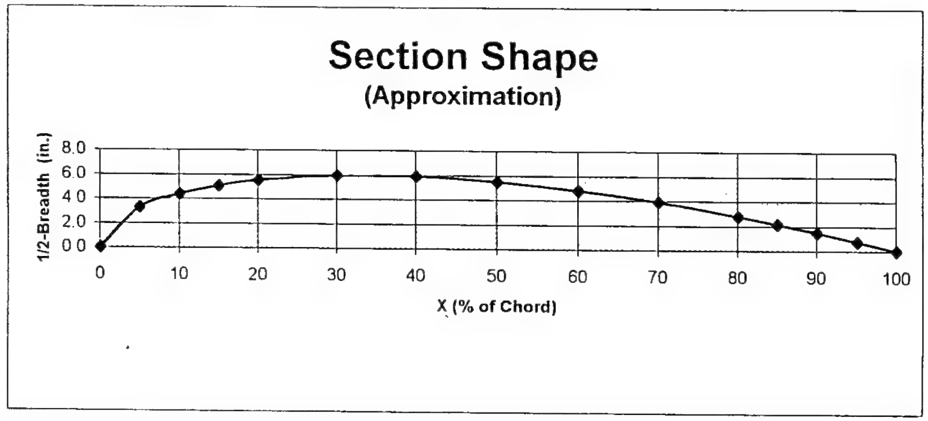
## Offsets & Related Claculations

**Station 1**

| | | |
|---|---|---|
| **Vertical positon:** | 5 | ft. from BL |
| **Max. Thickness:** | 11.875 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 29.75 | in. aft of fwd fitting |
| **Leading edge position:** | 0 | in. aft of fwd fitting |
| **Trailing edge position:** | 85 | in. aft of fwd fitting |

| X<br>% | 1/2 Breadth<br>non-dimensional | SM | Area<br>multiple | 1/2 Breadth<br>in (scaled) | (ft) |
|---|---|---|---|---|---|
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 13.0269 | 3.2567 | 0.271 |
| 10 | 0.0052 | 1 | 8.7659 | 4.3830 | 0.365 |
| 15 | 0.0060 | 2 | 20.2588 | 5.0647 | 0.422 |
| 20 | 0.0065 | 1.5 | 16.5419 | 5.5140 | 0.459 |
| 30 | 0.0070 | 4 | 47.3179 | 5.9147 | 0.493 |
| 40 | 0.0069 | 2 | 23.4135 | 5.8534 | 0.488 |
| 50 | 0.0064 | 4 | 43.6525 | 5.4566 | 0.455 |
| 60 | 0.0056 | 2 | 19.1188 | 4.7797 | 0.398 |
| 70 | 0.0046 | 4 | 30.9779 | 3.8722 | 0.323 |
| 80 | 0.0032 | 1.5 | 8.2769 | 2.7590 | 0.230 |
| 85 | 0.0025 | 2 | 8.5263 | 2.1316 | 0.178 |
| 90 | 0.0017 | 1 | 2.9252 | 1.4626 | 0.122 |
| 95 | 0.0009 | 2 | 3.0044 | 0.7511 | 0.063 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 245.8068 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| **Cl:** | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| **Cd:** | 0.0058 | 0 leeway | 0.0065 | 2 deg. Leeway | 0.0081 | 4 deg leeway |

**approx. LCp:** 21.25 in. aft of fwd fitting
**Chord:** 85 in.
**t/c:** 0.139
**Area:** 696.452 in²

**Most similar NACA section:** 00 14

# USNA 44-Foot Sloop Keel Re-Design

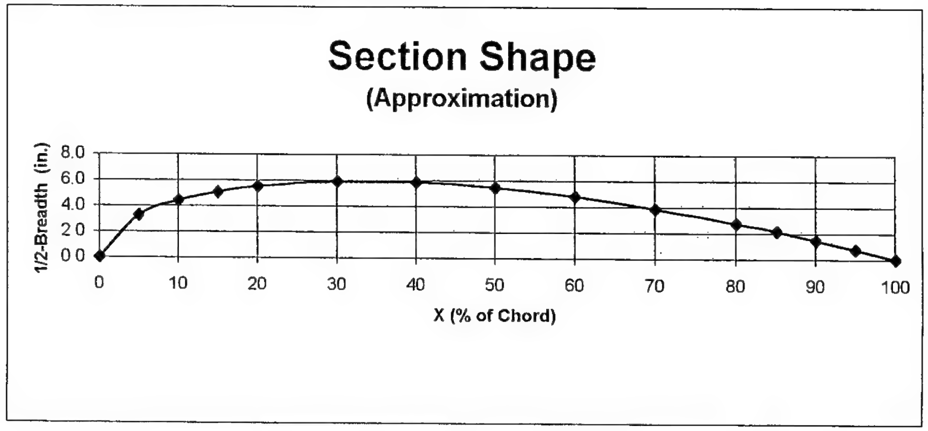
Offsets & Related Claculations

Station 2

| | | |
|---|---|---|
| **Vertical positon:** | 4.375 | ft. from BL |
| **Max. Thickness:** | 10.5 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 28.125 | in. aft of fwd fitting |
| Leading edge position: | 1.875 | in. aft of fwd fitting |
| Trailing edge position: | 76.875 | in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| **Cl:** | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| **Cd:** | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |
| **approx. LCp:** | 20.625 | in. aft of fwd fitting | | | | |
| **Chord:** | 75 | in. | | | | |
| **t/c:** | 0.139 | | | | | |
| **Area:** | 543.362 | $in^2$ | | | | |

**Most similar NACA section:** 00 14

# USNA 44-Foot Sloop Keel Re-Design

## Offsets & Related Claculations

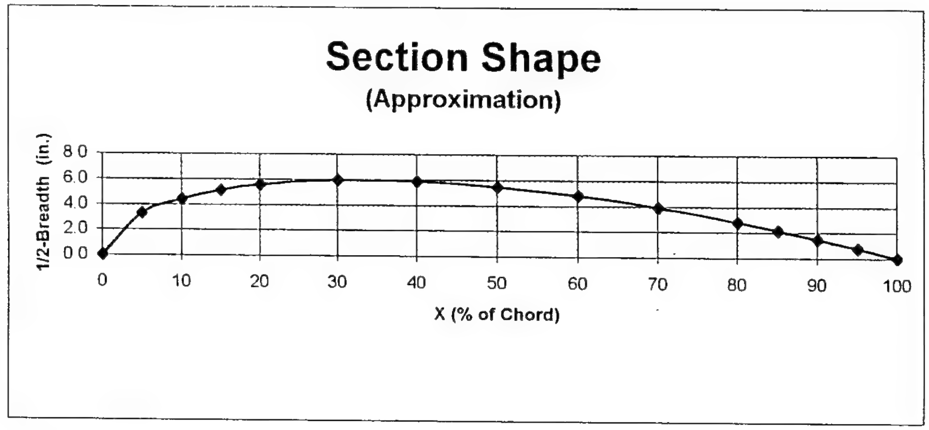
**Station 3**

| | | |
|---|---|---|
| **Vertical positon:** | 3.750 | ft. from BL |
| **Max. Thickness:** | 10.5 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 30 | in. aft of fwd fitting |
| **Leading edge position:** | 3.75 | in. aft of fwd fitting |
| **Trailing edge position:** | 78.75 | in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Cl:** | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| **Cd:** | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |
| **pprox. LCp:** | 22.5 in. aft of fwd fitting | | | | | |
| **Chord:** | 75 in. | | | | | |
| **t/c:** | 0.139 | | | | | |
| **Area:** | 543.362 in² | | | | | |
| **Most similar NACA section:** | 00 14 | | | | | |



# USNA 44-Foot Sloop Keel Re-Design

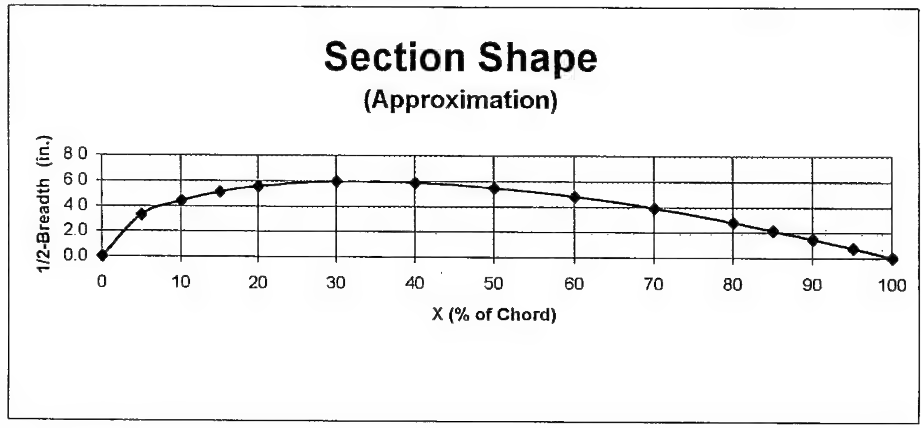
Offsets & Related Claculations

Station 4

| | | |
|---|---|---|
| Vertical positon: | 3.125 | ft. from BL |
| Max. Thickness: | 10.5 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 31.875 | in. aft of fwd fitting |
| Leading edge position: | 5.625 | in. aft of fwd fitting |
| Trailing edge position: | 80.625 | in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0,0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| Cl: | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| Cd: | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |

pprox. LCp: 24.375 in. aft of fwd fitting

Chord: 75 in.

t/c: 0.139

Area: 543.362 $in^2$

Most similar NACA section: 00 14

# USNA 44-Foot Sloop Keel Re-Design

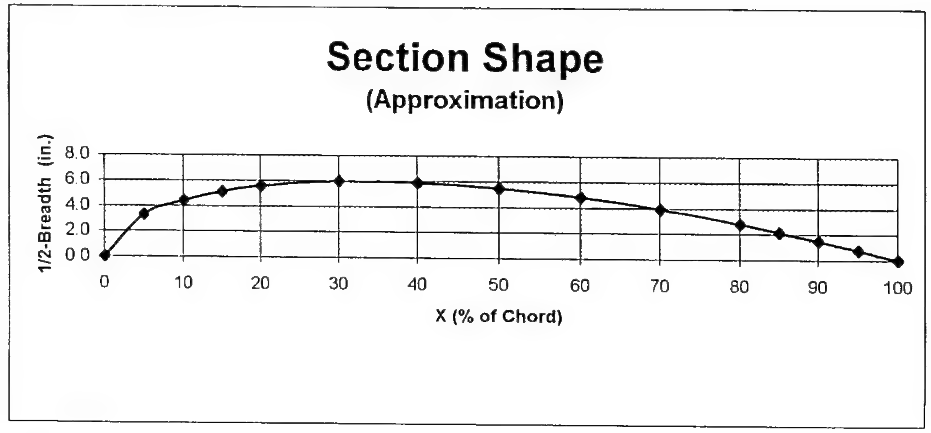
## Offsets & Related Claculations

**Station 5**

| | |
|---|---|
| **Vertical positon:** | 2.500 ft. from BL |
| **Max. Thickness:** | 10.5 in. |

| | |
|---|---|
| Location of max. thickness: | 33.75 in. aft of fwd fitting |
| **Leading edge position:** | 7.5 in. aft of fwd fitting |
| **Trailing edge position:** | 82.5 in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| **Cl:** | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| **Cd:** | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |

**pprox. LCp:** 26.25 in. aft of fwd fitting

**Chord:** 75 in.

**t/c:** 0.139

**Area:** 543.362 in²

**Most similar NACA section:** 00 14

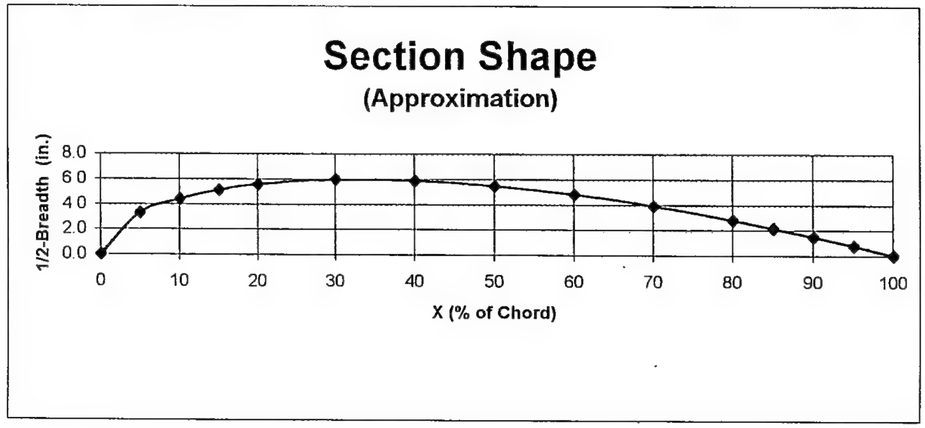
# USNA 44-Foot Sloop Keel Re-Design
## Offsets & Related Claculations

**Station 6**

| | | |
|---|---|---|
| **Vertical positon:** | 1.875 | ft. from BL |
| **Max. Thickness:** | 10.5 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 35.625 | in. aft of fwd fitting |
| Leading edge position: | 9.375 | in. aft of fwd fitting |
| Trailing edge position: | 84.375 | in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| **Cl:** | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| **Cd:** | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |
| **pprox. LCp:** | 28.125 | in. aft of fwd fitting | | | | |
| **Chord:** | 75 | in. | | | | |
| **t/c:** | 0.139 | | | | | |
| **Area:** | 543.362 | $in^2$ | | | | |

**Most similar NACA section:** 00 14

# USNA 44-Foot Sloop Keel Re-Design
Offsets & Related Claculations

**Station 7**

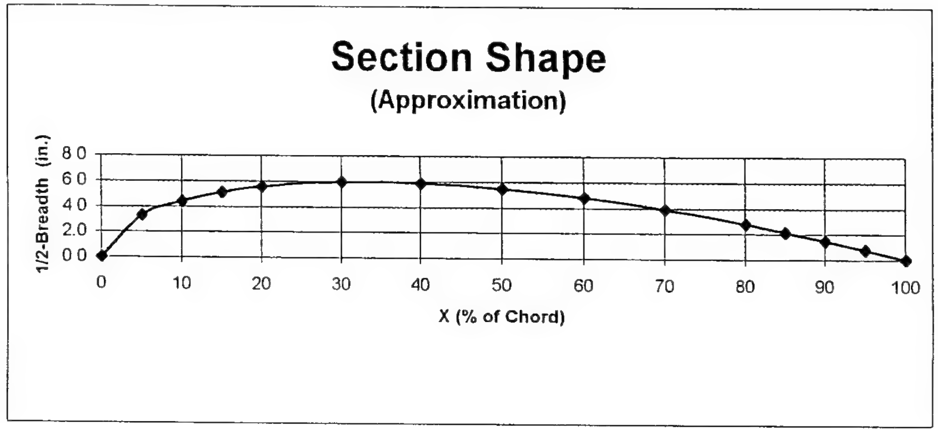
| | | |
|---|---|---|
| Vertical positon: | 1.250 | ft. from BL |
| Max. Thickness: | 10.5 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 37.5 | in. aft of fwd fitting |
| Leading edge position: | 11.25 | in. aft of fwd fitting |
| Trailing edge position: | 86.25 | in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Cl: | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| Cd: | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |

pprox. LCp: 30 in. aft of fwd fitting
Chord: 75 in.
t/c: 0.139
Area: 543.362 in²
Most similar NACA section: 00 14



# USNA 44-Foot Sloop Keel Re-Design

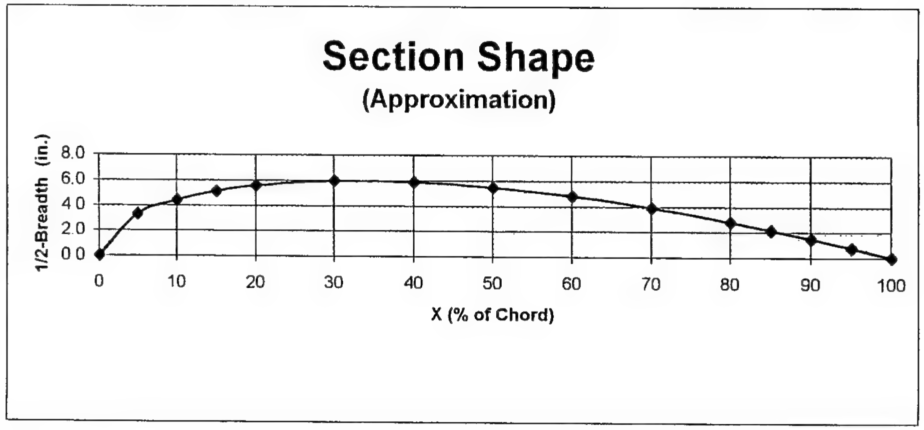
Offsets & Related Claculations

Station 8

| | |
|---|---|
| Vertical positon: | 0.625 ft. from BL |
| Max. Thickness: | 10.5 in. |

| | |
|---|---|
| Location of max. thickness: | 39.375 in. aft of fwd fitting |
| Leading edge position: | 13.125 in. aft of fwd fitting |
| Trailing edge position: | 88.125 in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| Cl: | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| Cd: | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |

pprox. LCp: 31.875 in. aft of fwd fitting

Chord: 75 in.

t/c: 0.139

Area: 543.362 in²

Most similar NACA section: 00 14

# USNA 44-Foot Sloop Keel Re-Design

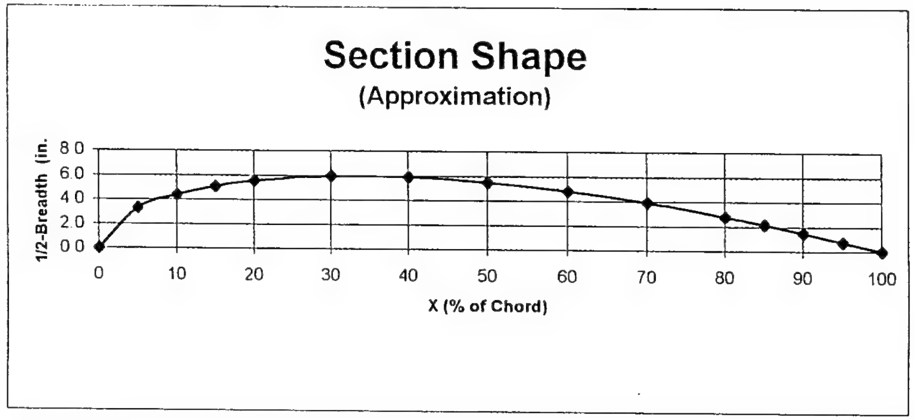
## Offsets & Related Claculations

**Station 9**

| | | |
|---|---|---|
| Vertical positon: | 0.000 | ft. from BL |
| Max. Thickness: | 10.5 | in. |

| | | |
|---|---|---|
| Location of max. thickness: | 41.25 | in. aft of fwd fitting |
| Leading edge position: | 15 | in. aft of fwd fitting |
| Trailing edge position: | 90 | in. aft of fwd fitting |

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | |
|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | (ft) |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| 5 | 0.0038 | 2 | 11.5185 | 2.8796 | 0.240 |
| 10 | 0.0052 | 1 | 7.7509 | 3.8755 | 0.323 |
| 15 | 0.0060 | 2 | 17.9130 | 4.4783 | 0.373 |
| 20 | 0.0065 | 1.5 | 14.6265 | 4.8755 | 0.406 |
| 30 | 0.0070 | 4 | 41.8390 | 5.2299 | 0.436 |
| 40 | 0.0069 | 2 | 20.7025 | 5.1756 | 0.431 |
| 50 | 0.0064 | 4 | 38.5980 | 4.8248 | 0.402 |
| 60 | 0.0056 | 2 | 16.9050 | 4.2263 | 0.352 |
| 70 | 0.0046 | 4 | 27.3910 | 3.4239 | 0.285 |
| 80 | 0.0033 | 1.5 | 7.3185 | 2.4395 | 0.203 |
| 85 | 0.0025 | 2 | 7.5390 | 1.8848 | 0.157 |
| 90 | 0.0017 | 1 | 2.5865 | 1.2933 | 0.108 |
| 95 | 0.0009 | 2 | 2.6565 | 0.6641 | 0.055 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 |
| | | | 217.3449 | | |




| | | | | | | |
|---|---|---|---|---|---|---|
| Cl: | 0 | 0 leeway | 0.2 | 2 deg. Leeway | 0.41 | 4 deg leeway |
| Cd: | 0.0095 | 0 leeway | 0.0096 | 2 deg. Leeway | 0.0102 | 4 deg leeway |

**approx. LCp:** 33.75 in. aft of fwd fitting

**Chord:** 75 in.

**t/c:** 0.139

**Area:** 543.362 in²

**Most similar NACA section:** 00 14

# Bulb Calculations

| | |
|---|---|
| Vertical positon: | 0.000 ft. from BL |
| Max. Thickness: | 17.25 in. |

| | |
|---|---|
| Location of max. thickness: | 61 5 in. aft of fwd fitting |
| Leading edge position: | 30 in. aft of fwd fitting |
| Trailing edge position: | 126 in. aft of fwd fitting |

Keel Base

| X | 1/2 Breadth | SM | Area | 1/2 Breadth | Added area | vol. Calc | VCG |
|---|---|---|---|---|---|---|---|
| % | non-dimensional | | multiple | in (scaled) | in^2 | in^2 | multiple |
| 0 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 | 0 000 | 0.000 |
| 5 | 0.0049 | 2 | 18 9233 | 4.7308 | 16.738 | 33.476 | 74.974 |
| 10 | 0.0066 | 1 | 12.7337 | 6.3668 | 28.966 | 28 966 | 72.164 |
| 15 | 0.0077 | 2 | 29.4285 | 7.3571 | 38.677 | 77 354 | 222.692 |
| 20 | 0.0083 | 1.5 | 24.0293 | 8.0098 | 45.843 | 68.765 | 215.526 |
| 30 | 0.0089 | 4 | 68.7355 | 8.5919 | 52.749 | 210.998 | 709.388 |
| 40 | 0.0089 | 2 | 34.0113 | 8.5028 | 51.661 | 103.322 | 343.770 |
| 50 | 0.0083 | 4 | 63.4110 | 7.9264 | 44.894 | 179 575 | 556 974 |
| 60 | 0.0072 | 2 | 27.7725 | 6.9431 | 34.447 | 68.893 | 187.174 |
| 70 | 0.0059 | 4 | 44.9995 | 5.6249 | 22.608 | 90 434 | 199 051 |
| 80 | 0.0042 | 1.5 | 12.0233 | 4 0078 | 11.477 | 17.216 | 26.999 |
| 85 | 0.0032 | 2 | 12.3855 | 3.0964 | 6 851 | 13.702 | 16 601 |
| 90 | 0.0022 | 1 | 4.2493 | 2.1246 | 3.226 | 3 226 | 2.682 |
| 95 | 0.0011 | 2 | 4.3643 | 1.0911 | 0.851 | 1.701 | 0.726 |
| 100 | 0.0000 | 0.5 | 0.0000 | 0.0000 | 0.000 | 0.000 | 0.000 |
| | | | 357.0667 | | | 897.626 | 2628.721 |

| | | | |
|---|---|---|---|
| Cl: | 0.000 0 leeway | 0.200 2 deg. Leew | 0.410 4 deg leeway |
| Cd: | 0.010 0 leeway | 0.010 2 deg. Leew | 0.010 4 deg leeway |

approx. LCp: 54 in. aft of fwd fitting
Chord: 96 in.
t/c: 0.179
Area: 1142.613 in²
Most similar NACA section: 00 18

| | |
|---|---|
| Added Volume: | 2872.40 in^3 |
| Added Weight: | 1180.21 lb |
| Centroid of Added Mass: | 2.93 in. from keel base |

x=0
Theo. Bulb height 0 in
keel/bulb intersect 0 in

x=5
Theo. Bulb height 14 19244 in
keel/bulb intersect 6.718873 in

x=10
Theo. Bulb height 19 10049 in
keel/bulb intersect 7.474106 in

x=15
Theo. Bulb height 22.071375 in
keel/bulb intersect 8.636625 in

x=20
Theo. Bulb height 24.02925 in
keel/bulb intersect 9 40275 in

x=30
Theo Bulb height 25.77581 in
keel/bulb intersect 10 08619 in

x=40
Theo. Bulb height 25.5084375 in
keel/bulb intersect 9.9815625 in

x=50
Theo. Bulb height 23 77913 in
keel/bulb intersect 9.304875 in

x=60
Theo. Bulb height 20.82938 in
keel/bulb intersect 8.150625 in

x=70
Theo Bulb height 16.8748125 in
keel/bulb intersect 6.6031875 in

x=80
Theo Bulb height 12.02325 in
keel/bulb intersect 4.70475 in

x=85
Theo. Bulb height 9.289125 in
keel/bulb intersect 3.634875 in

x=90
Theo. Bulb height 6.373875 in
keel/bulb intersect 2.494125 in

x=95
Theo Bulb height 3.273188 in
keel/bulb intersect 1.280813 in

x=100
Theo Bulb height 0 in
keel/bulb intersect 0 in

# USNA 44-Foot Sloop Keel Re-Design

## Initial Data Analysis

Design speed 6 kts 10.127 ft/s

Salt water @ STP

Mass density of water: 1.9905 lb*s^2/ft^4

| | | |
|---|---|---|
| Keel CG: | 48.55 | in. |
| KG (boat): | 78.50 | in. |
| Keel Height: | 60.00 | in. |
| Spacing: | 7.50 | in. |
| Volume: | 32984.46 | in³ |
| Long. Cp: | 26.33 | in. |
| 1/2 Area: | 4525.00 | in² |
| Aspect Ratio: | 0.788 | |

| | | |
|---|---|---|
| Keel stubby ht: | 20 | in. |

| | Station | Area | C | LCp | SM | Volume Product | Area Product | LCp Product | Area MT Product | Righting Product | CG multiple | Mass MT Product |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Connection | 1 | 696.452 | 85.000 | 21.25 | 1 | 696.45 | 85.00 | 1806.25 | 202.02 | 5293.93 | 0.00 | 97937.62 |
| | 2 | 543.362 | 75.000 | 20.625 | 4 | 2173.45 | 300.00 | 6187.50 | 1408.33 | 23218.68 | 0.00 | 603685.59 |
| | 3 | 543.362 | 75.000 | 22.5 | 2 | 1086.72 | 150.00 | 3375.00 | 1169.01 | 14958.19 | 16744.24 | 501099.23 |
| | 4 | 543.362 | 75.000 | 24.375 | 4 | 2173.45 | 300.00 | 7312.50 | 3502.08 | 36614.07 | 37674.54 | 1501176.74 |
| | 5 | 543.362 | 75.000 | 26.25 | 2 | 1086.72 | 150.00 | 3937.50 | 2450.26 | 21655.88 | 50232.71 | 1050310.23 |
| | 6 | 543.362 | 75.000 | 28.125 | 4 | 2173.45 | 300.00 | 8437.50 | 6533.33 | 50009.46 | 62790.89 | 2800529.61 |
| | 7 | 543.362 | 75.000 | 30 | 2 | 1086.72 | 150.00 | 4500.00 | 4200.26 | 28353.58 | 75349.07 | 1800452.09 |
| | 8 | 543.362 | 75.000 | 31.875 | 4 | 2173.45 | 300.00 | 9562.50 | 10502.08 | 63404.85 | 87907.25 | 4501744.18 |
| Baseline | 9 | 543.362 | 75.000 | 33.75 | 1 | 543.36 | 75.00 | 2531.25 | 3209.51 | 17525.64 | 100465.43 | 1375762.40 |
| Sums: | | | 685.00 | | | 13193.79 | 1810.00 | 47650.00 | 33176.89 | 261034.25 | 498520.56 | 14232697.70 |

### Leeway Angle = 0 degrees

| Cl | Cd | Lift Product | Drag Product | Arm Product |
|---|---|---|---|---|
| 0 | 0.0058 | | | |
| 0 | 0.0095 | 0.000 | 4.590 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| 0 | 0.0095 | 0.000 | 5.344 | 0 |
| | | 0.00 | 42.00 | 0 |

| | | |
|---|---|---|
| Lift: | 0.000 | lb |
| Drag: | 29.767 | lb |
| VCp | #DIV/0! | in. |

### Leeway Angle = 2 degrees

| Cl | Cd | Lift Product | Drag Product | Arm Product |
|---|---|---|---|---|
| 0.2 | 0.0065 | | | |
| 0.2 | 0.0096 | 120.00 | 4.830 | 318.9568 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 897.0659 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 1495.11 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 2093.154 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 2691.198 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 3289.242 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 3887.286 |
| 0.2 | 0.0096 | 112.50 | 5.400 | 4485.33 |
| | | 907.50 | 42.63 | 19157.34 |

| | | |
|---|---|---|
| Lift: | 643.229 | lb |
| Drag: | 30.216 | lb |
| VCp | 29.783 | in. |
| Lift (w/ AR): | 234.76 | lb |

### Leeway Angle = 4 degrees

| Cl | Cd | Lift Product | Drag Product | Arm Product |
|---|---|---|---|---|
| 0.41 | 0.0081 | | | |
| 0.41 | 0.0102 | 246.00 | 5.490 | 653.8614 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 1838.985 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 3064.975 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 4290.965 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 5516.955 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 6742.945 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 7968.935 |
| 0.41 | 0.0102 | 230.63 | 5.738 | 9194.926 |
| | | 1860.38 | 45.65 | 39272.55 |

| | | |
|---|---|---|
| Lift: | 1318.620 | lb |
| Drag: | 32.358 | lb |
| VCp | 29.783 | in. |
| Lift (w/ AR): | 481.25 | lb |

**Old Keel Properties:**

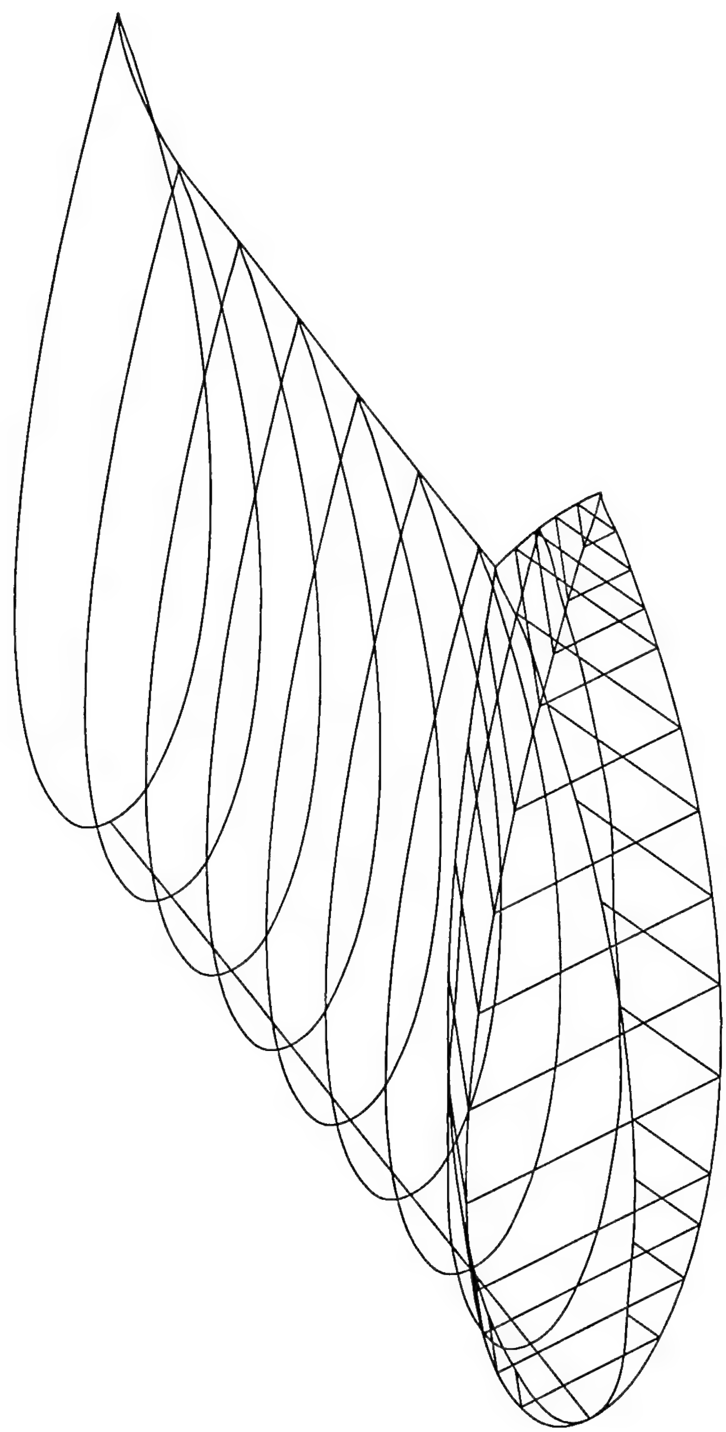
| | | |
|---|---|---|
| Planform area: | 4902.66 | in^2 |
| Weight | 12310 | lb |
| CG (From keel root) | 27.58 | in |
| Mass MT of inertia | 3.02E+05 | lb-ft^2 |
| Righting MT about KG | 5.65E+04 | ft-lb. |
| Area MT of inertia | 672.01 | ft^4 |
| Drag @ 0 leeway | 32.96 | lb |
| Ideal Lift @ 2 deg leeway | 693.67 | lb |
| True Lift @ 2 deg leeway | 207.23 | lb |

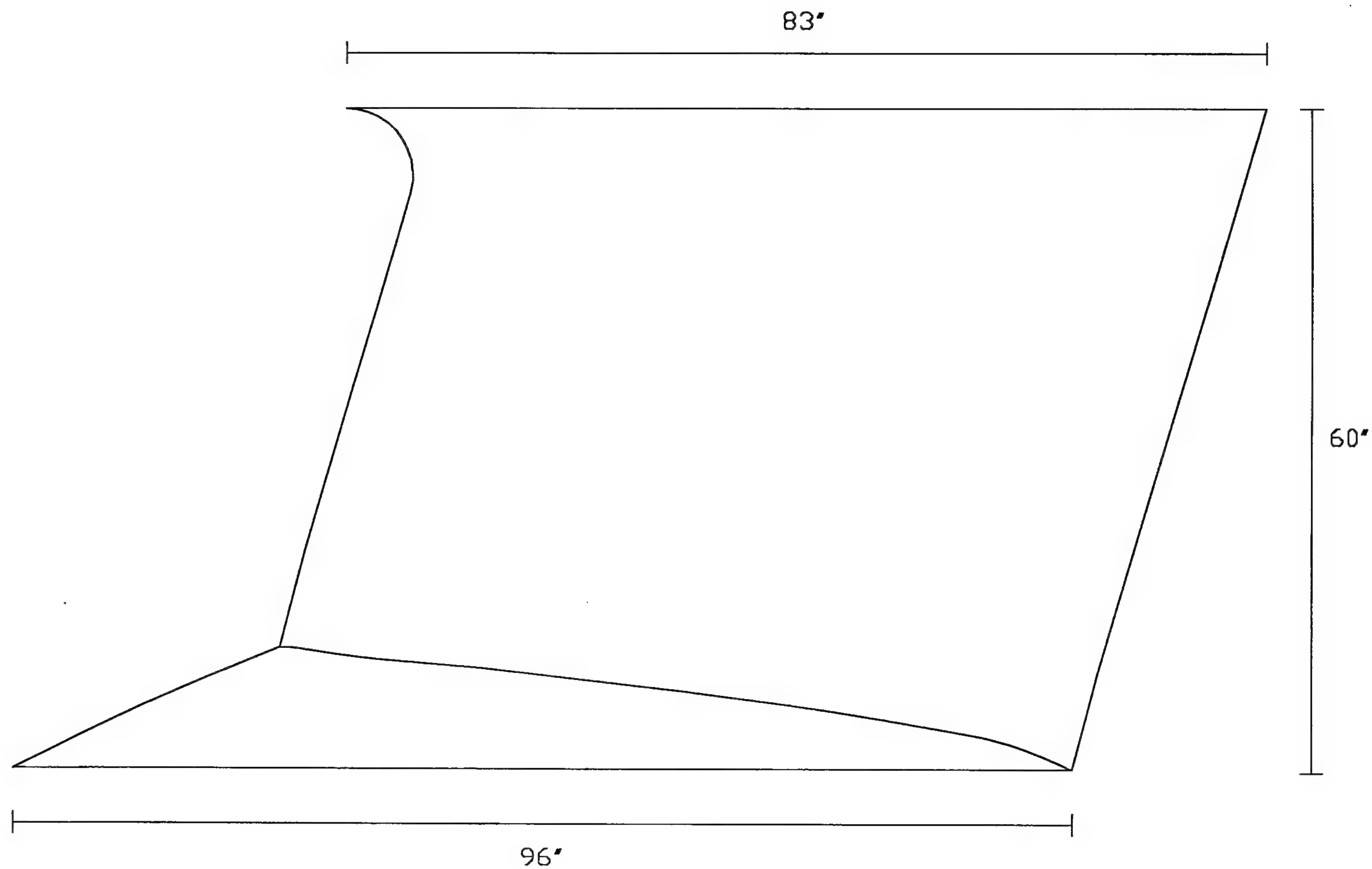
**New Keel Properties:**

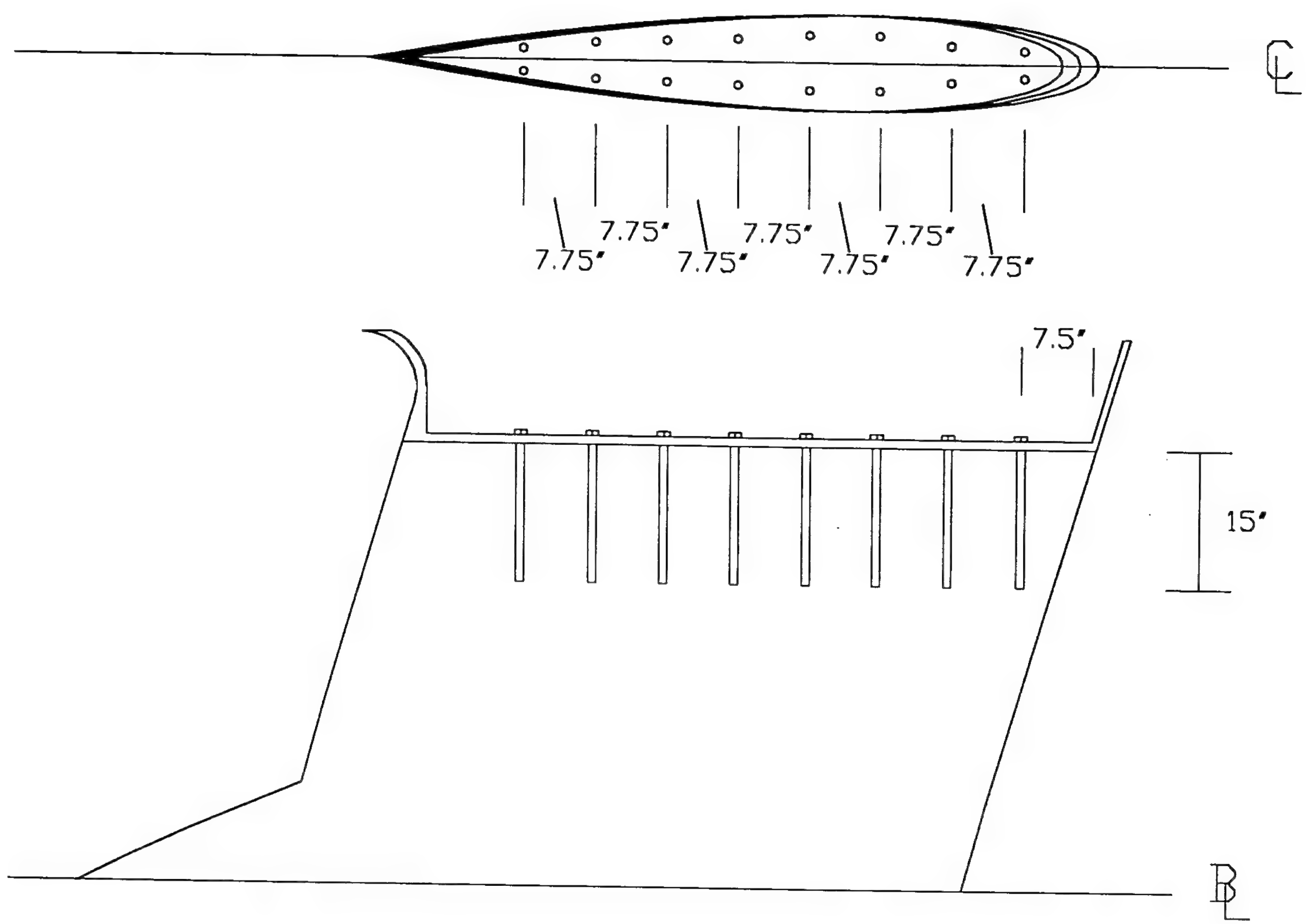
| | | |
|---|---|---|
| Planform area: | 4525.00 | in^2 |
| Weight | 10268 | lb |
| CG (From keel root) | 48.55 | in |
| Mass MT of inertia | 2.47E+05 | lb-ft^2 |
| Righting MT about KG | 5.74E+04 | ft-lb. |
| Area MT of inertia | 575.99 | ft^4 |
| Drag @ 0 leeway | 29.77 | lb |
| Approx. leeway for equivalent lift | 2.05 | deg |
| Approx. leeway for equivalent lift | 1.68 | deg |

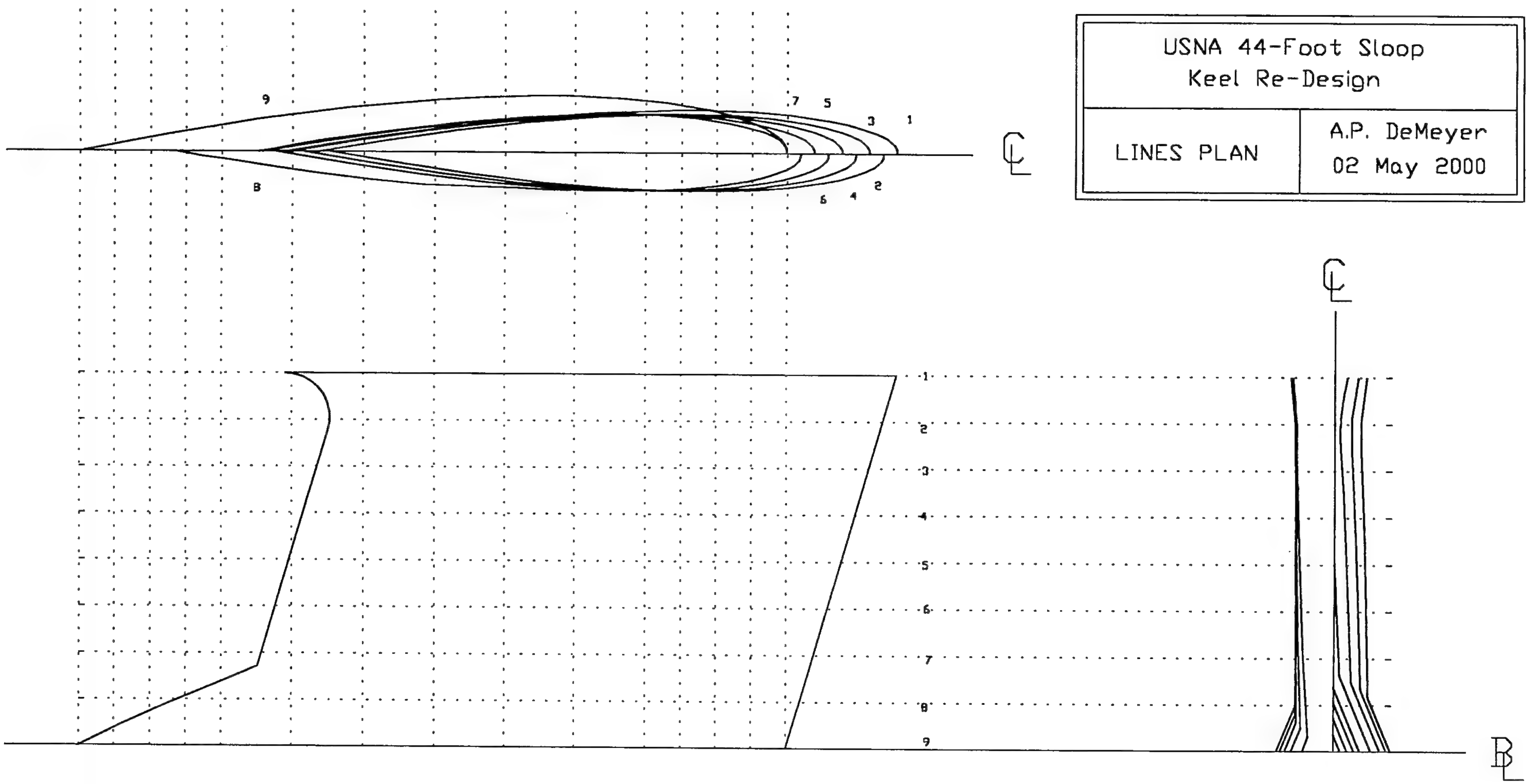
**Keel Bolt Parameters:**

| | | |
|---|---|---|
| number of bolts: | 16 | |
| Keel bolt load: | 25669.32 | lb |
| Keel bolt diameter: | 0.875 | in |
| Tensile strength/bolt: | 27704 | lb |
| Sheer strength/bolt: | 16027 | lb |
| Max sheer/bolt | 1687.5 | lb |

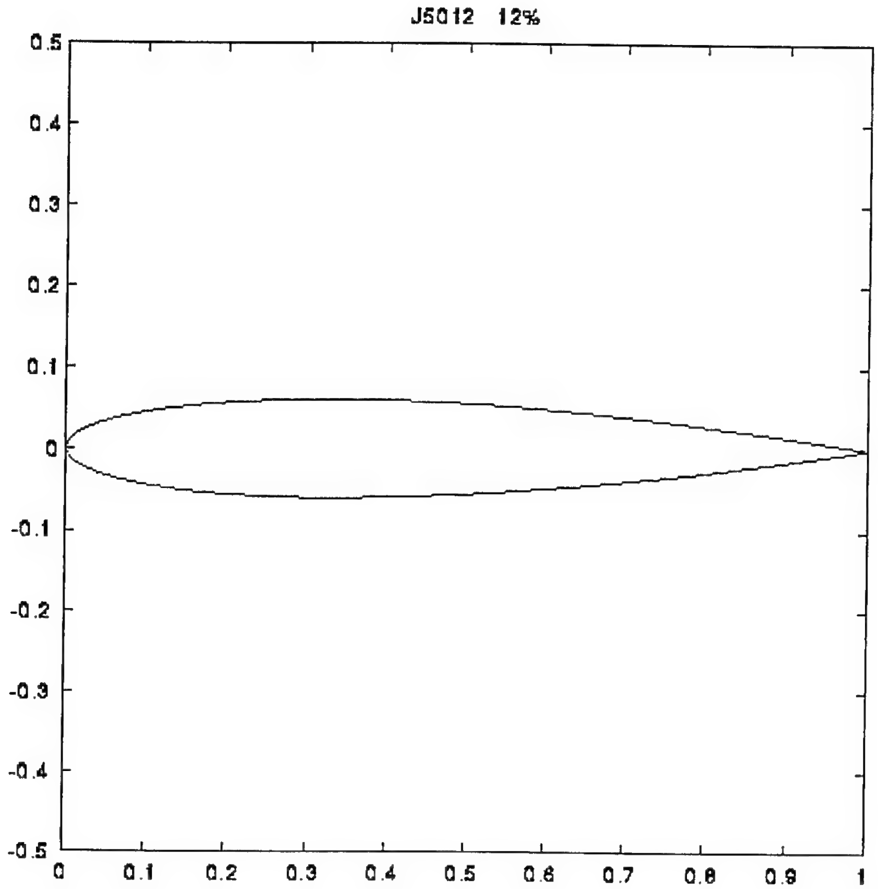


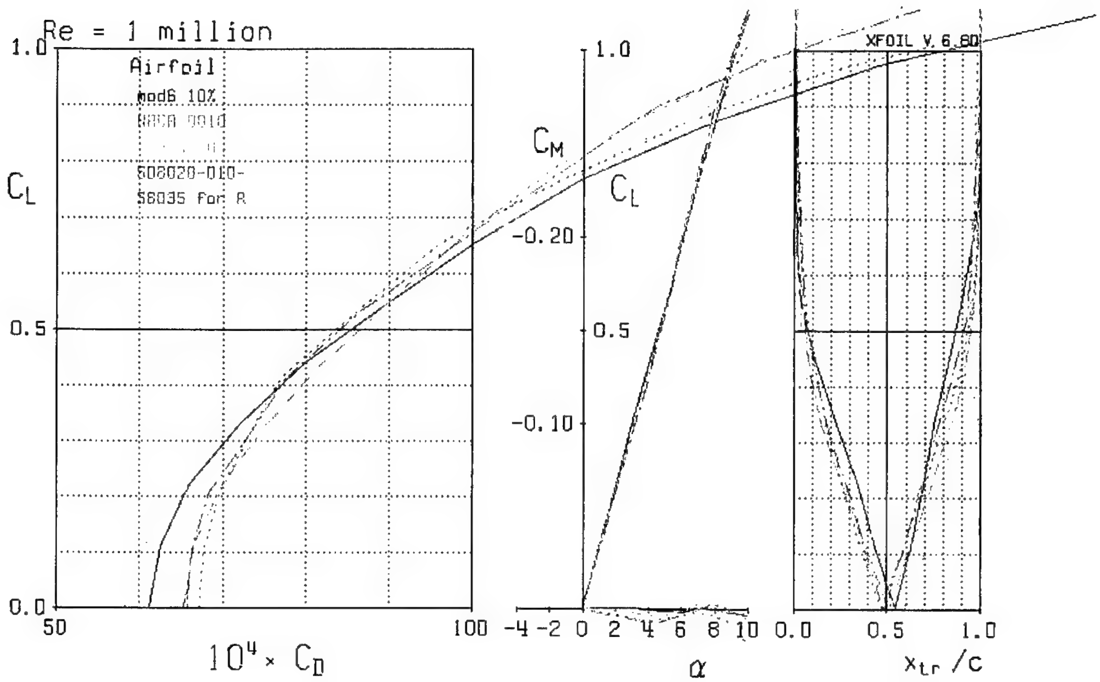

83″
60″
96″


7.75"
7.75"
7.75"
7.75"
7.75"
7.75"
7.75"
7.5"
15"



USNA 44-Foot Sloop
Keel Re-Design
LINES PLAN
A.P. DeMeyer
02 May 2000


J5012 12%
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1




Comparison of lift and drag characteristics of different foil sections. In the typical lift coefficient range for the Navy 44 (0.0-0.35), the J5012/J5013 has lower drag. (Figure and analysis courtesy of Paul Bogataj.)

# Navy-44 Full-Scale Resistance Test

ENS A.P. DeMeyer, USNR

21 August, 2000

## INTRODUCTION:

Resistance testing is used to determine the powering requirements for a given vessel. Normally conducted in a towing tank with scale models for accuracy, under certain weather conditions, resistance testing of full-size vessels is not only possible, but perhaps more accurate than towing tests. This study examines the results of a resistance test conducted in the Severn River on the morning of 21 August, 2000 with the McCurdy and Rhodes 44-foot sloop, as well as a comparison to recent VPP predictions of resistance for the same hull form. Results showed that the VPP underestimates but remains consistent with experimentally obtained values.

## SETUP:

For this experiment, a 500-lb load cell was attached to the forward mooring cleats of a Navy-44, with the other end attached to a long Spectra™ towline. The towline was then connected to a powerboat in the Naval Station fleet. Power for the load cell was provided by the 12-volt outlet aboard the sailboat, connected to a 300-watt inverter. A 40-foot 12-volt extension cable was needed so that the instruments could safely be set up on the foredeck of the boat. A laptop computer was then also plugged into the inverter for recording and analyzing data. Two handheld VHF radios provided communications, and a hand-held GPS receiver was used for speed information (a result of the ending of selective availability).

## PROCEDURE:

After rigging the towline, the GPS was turned on and allowed to track on the satellites. After zeroing the load cell, the vessel was towed up the river (against the current, which was very weak) at varying speeds. At each speed, the measured resistance was recorded. After gathering upstream data, the boat was again towed, this time, downriver. Again, resistance was recorded at various speeds. A graph of the raw data was processed on the laptop computer so that any unrefined points in the curve could be further refined. For the first two runs, the tests were conducted with the prop aligned vertically so as to minimize resistance. For the third and fourth, the prop was freely rotating as it would for a typical cruise with CSNTS.

## DISCUSSION:

Towing vessels can provide very useful information. Knowing how much force is required to pull a vessel at a given speed also means knowing how much horsepower is required to do the same job. Given propeller, shaft, gearing, and engine efficiencies, it then becomes possible to determine the size and type of motor required to power a vessel at target speeds. In the case of the Navy-44 design project, the current drive train is already known, but it becomes important to judge whether or not future boats might be able to use the same motor (or even a less powerful, less expensive one with lower fuel consumption).

Resistance is also a very good indicator of performance. Assuming all other factors affecting boat design remain constant, comparing resistance values for two designs will determine which boat is faster. What that means is that if two boats have the same displacement, sail plan, rigging, center of gravity, and seakeeping properties but one has greater measured resistance in tests, that boat will be slower and require more horsepower or more wind to meet the same speed. Also, since resistance curves are exponential, small decreases in resistance can sometimes amount to large speed benefits.

As the research data will indicate, there are also differences between measured and theoretical values for resistance. VPP data is usually fairly optimistic with regard to resistance, in part due to the parameters input into the system. For instance, VPP testing conducted in conjunction with this project did not account for the existence of a shaft and prop under the hull. This can account for a large portion of the total drag. Also, the VPP assumes that the boat has no bio-fouling. Though the Navy-44 tested had been cleaned by divers three days before the test, a reasonable assumption that some additional resistance was caused by sea life can be made. Also, the VPP used in the previous study assumes a hydrodynamically smooth hull, which is not achievable in the current hull due to the use of bottom paint. As has been stated before in other reports, however, this does not mean that VPP data cannot serve a purpose. It is likely that the error in the VPP predictions is consistent for all three boat designs, and so the measure of performance is accurate, *relative to the VPP data for the original boat*. In addition, modifications to the shaft and props used in the current boat, as well as advances in bottom smoothness, may account for additional savings in resistance.

COMMENTS AND SUGGESTIONS FOR FURTHER STUDY:

Two things could have happened to make the research data a little more accurate. First, though the Navy-44 tested had had its bottom cleaned by divers just three days earlier, the boat could have been hauled and sprayed, or even wet-sanded and launched just prior to testing. This would have ensured the most accurate measurement of resistance possible (Though under normal conditions, CSNTS boats would probably have *more* bio-fouling than in our test conditions). Second, the boat was tested more in a half-load than a full-load condition. The fuel tanks were full, but the water tanks were not completely full, and there were no food or provisions aboard the vessel. This had a minimal effect on resistance, but for complete accuracy, it would have been nice to have a fully loaded boat.

Proper communications is the key to running this experiment. Two helmsmen (one for each boat) must coordinate together to keep the towline straight, and this requires all participants to know what is going on at the time of testing. This can only be accomplished through proper communications.

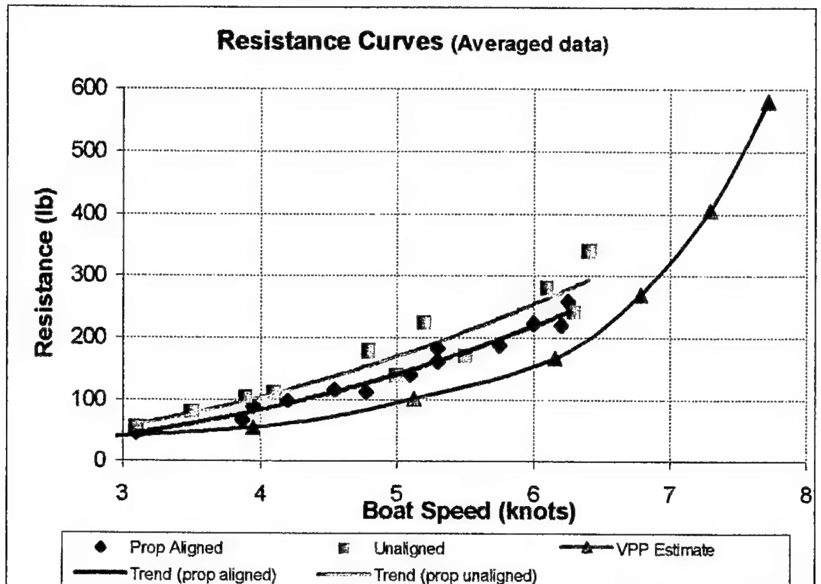
Wake from the towing vessel cannot be discounted for its effects on resistance. The towline was only about 100 feet in length and the boat was towed behind the towing vessel. This effect could have been minimized if the boat were to be towed with a tow bar alongside the towing vessel. Perhaps in the future, the apparatus will be available for such a test.

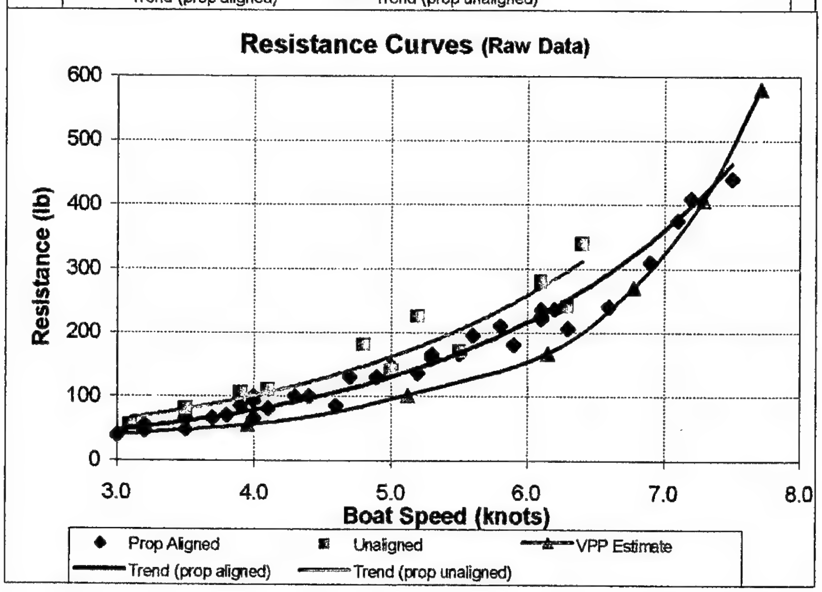
A final suggestion for attaining accurate results is to conduct testing in the flattest water available. Much of this test was performed upriver from the Route 50 Bridge on the Severn. This proved to be very flat water, and the early morning hour ensured little river

traffic. Test conditions were next to ideal, and further testing should endeavor to equal or surpass such conditions. A wise precaution here, however, is to remember to acquire data both heading upriver and downriver. This will negate current effects.

CONCLUSIONS:

As expected, resistance values for the current Navy-44 as gathered in this towing test were above the predicted VPP resistance values. As the graphs indicate, however, the shape of the two curves is fairly consistent. At middle speed ranges (between 4-6 knots) this difference is the most pronounced, likely due to the added resistance of the shaft and propeller blades. The green curves on the graphs indicate the resistance of the current boat with the propeller free to rotate, rather than "aligned" in the manner that the Varsity Offshore Sailing Team is taught to set the prop. The curve indicates a similar addition in resistance to that found between the aligned-prop version and the VPP estimate. This is significant in that it indicates that savings in resistance may be achieved by assessing the performance and resistance of the current prop and perhaps changing the prop to one with less resistance in idle.




Since the graphs also confirm the general shape of the resistance curve obtained in VPP predictions, it would also be reasonable to conclude that the VPP data for the two suggested designs is also valid. Any error in the predicted curve would likely follow the error between the towing of the current boat and its own VPP predictions. This would seem to indicate, therefore, that the two suggested designs from VPP predictions are still worth a more serious examination and consideration for replacements for the current design.

# VPP Performance Predictions for Current and Two Proposed Navy-44 Designs

ENS A. P. DeMeyer, USNR

## INTRODUCTION:

VPP (velocity prediction program) analysis is used to predict the speed of sailing vessels in realistic conditions. VPP programs use hull, rig and appendage parameters of the boat to produce numerical predictions of several performance and speed-related features of the boat. For this study, VMG (velocity made good) upwind and downwind performance, pure boat speed, and resistance values are compared between the current Navy-44 and two proposed design configurations. Results showed that significant improvements in boat speed, VMG, and resistance can be achieved through modifications to the current hull form and appendages.

## SETUP:

The VPP used for this study was developed by Chris Todter to improve the performance of boat designs for an American syndicate for the most recent America's Cup. With detailed input parameters, this VPP gives perhaps the most accurate assessment of boat performance available without actually building and testing a model or full-size boat. The program runs on an Excel spreadsheet, is easy to load and use, but requires a fast processor and a good deal of RAM to run efficiently. A second spreadsheet is required to download data.

## PROCEDURE:

The first step for this study was to develop performance specifications for the existing Navy-44. IMS ratings sheets, phone calls, and a little legwork were required to gather the necessary data. Hull, keel, rudder, and rig parameters were adjusted to meet the current boat's specs. Roll moment was also adjusted to fit inclining experiment Navy-44 parameters (see "Navy 44 Inclining Experiment [7 AUG 2000] Discussion and Results", A.P. DeMeyer, 2000), and the crew weight was taken into account as well.

At this point, the VPP was run. This study focused on three wind speeds (6, 12, and 24 knots), but to achieve the largest amount of original data possible, all speeds were selected for the initial run. Results were then recorded on a separate spreadsheet for later analysis.

This process was followed again in successive runs involving single- or limited-parameter changes to the current design to gauge the performance changes of different modifications. Finally, two combinations of changes (labeled "Mid-line" and "Performance") were tested to determine if the combined modifications would have a beneficial effect on boat performance. Each time, the pertinent data (VMG, boat speed, wind angle, heel, and thrust) were recorded and placed in a separate spreadsheet to preserve the data for analysis.

The following table outlines the changes to the hull form and appendages during the study:

| CHARACTERISTIC | BOAT | VALUE |
|---|---|---|
| LOA: | All | 44 ft. |
| LWL: | current | 34.125 ft. |
| | mid-line | 38.5 ft. |
| | performance | 41 ft. |
| Displacement: | current | 28598 lb. |
| | mid-line | 25000 lb. |
| | performance | 23468 lb. |
| Canoe body depth: | current | 3 ft. |
| | mid-line | 2.5 ft. |
| | performance | 2.25 ft. |
| Canoe body volume: | current | 254.66 ft^3 |
| | mid-line | 230.19 ft^3 |
| | performance | 206.25 ft^3 |
| Type of keel: | current | current keel |
| | mid-line | Spring 2000* |
| | performance | Spring 2000* |
| Righting moment: | current | current value |
| | mid-line | 1.15*current value** |
| | performance | 1.15*current value** |

* The Spring 2000 keel design refers to a higher aspect ratio keel with an IMS bulb developed for the new Navy 44 (see "USNA 44-Foot Sloop Keel Re-Design Project", A.P. DeMeyer, 2000).

** This value is a result of the new keel's lower CG. This may be a conservative estimate, as any laminate changes are likely to lower the KG of the boat as well (in full load).

Data for the multiple runs was then analyzed and graphically represented in the second spreadsheet. Several polar plots directly compared true boat speed at given wind speeds. In addition, bar graphs of VMG comparisons and VMG improvements were created. Finally, a single resistance comparison graph was developed.

DISCUSSION:

The benefit of a VPP is that multiple runs of multiple configurations can be made without producing models. This is an enormously effective tool, as it allows a designer to make several changes to a hull form and optimize a shape without actually spending the

money on models and towing tank time. Further testing in a towing tank then builds on VPP data, and a more limited amount of time and resources is used in the follow-on tests.

Common sense and training dictate that certain generalized changes in hull shape and appendages should change performance in given ways. What is never clear, however, is how those changes will interact. Furthermore, any given change to a hull or appendages invariably changes other aspects of the design. For example, changing the displacement of the boat will likely change the submerged volume, block coefficient, wetted surface area, and stability. For this reason, any changes in the boat's parameters needs to be analyzed, and a best estimate of other changes should be taken into account as well. There are inherent flaws in data of this nature, but not of the magnitude as to make the data unusable. Flaws are minimized by changing as few parameters as possible and documenting changes when made.

In general, lengthening the waterline will increase speed. This is due to the lower Froude numbers achieved in making wetted length longer. Other beneficial changes include general weight reduction, increased stability, changes to appendage shapes (and weight distributions), and changes to the hull shape. The current boat design is relatively heavy, and the underwater hull form includes a very round-bilged canoe body and a plain deep keel of low aspect ratio and high CG. Weight savings and hydrodynamic shaping of the hull can produce a less rounded bottom and higher aspect ratio keel with an IMS bulb. This should (and results proved *does*) produce a faster and more stable boat.

The two proposals (labeled "Mid-line" and "Performance") are a result of critical thinking about the two major programs tied to Navy sailing. The Varsity Offshore Sailing Team (VOST) would like to dramatically improve the speed and handling performance of the vessel. Hardly an unlikely suggestion, the VOST program would like to have fast boats for competition sailing (hence the performance proposal). The CSNTS program, on the other hand, relies on the ability of novice sailors to easily learn the systems and requires more safety features (hence the mid-line approach). Neither of the suggested hull forms is radical in design, and neither stretches safety limits for offshore sailing. In fact, both actually show measured improvement in stability calculations. And importantly, both designs fit within the requirement for overall length, draft, and the requirement to maintain the same sail plan and rigging.

## COMMENTS AND SUGGESTIONS FOR FURTHER STUDY:

The best way to achieve more accurate data would be to start with a whole new design. Given new offsets and a better idea of displacement and appendage locations and specifications, the input parameters would be more accurate, making data fit true design specs. Unfortunately, the time involved in developing new data is prohibitive.

A good way to acquire more data, however, would be to simply change more parameters, and to do so in the same manner as has been done in this limited study. More parameters, perhaps changed in graded amounts, can quantify the potential performance benefits of given changes. This could be useful if curves were developed for optimizing the hull form, though the amount of runs necessary for finding the data would be mind-boggling.

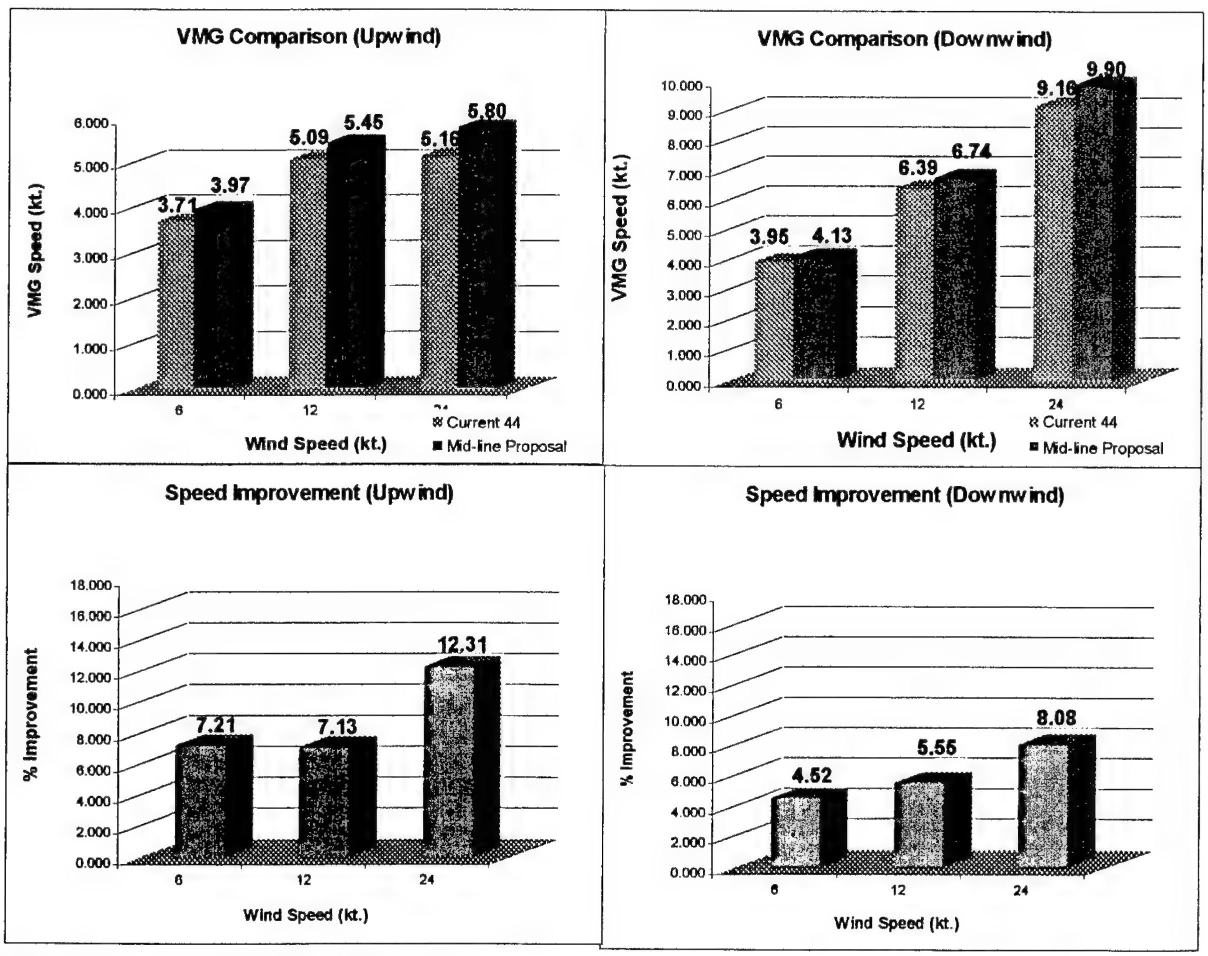
Perhaps the best way to build on this data would be to design hull forms to fit the parameters used for these two proposed hulls, build models, and tow them. Likely, small

differences between the computer model and tow tank tests would exist, but just as likely, the model tests will prove the computer theory that the suggested changes will produce a faster, more stable boat.

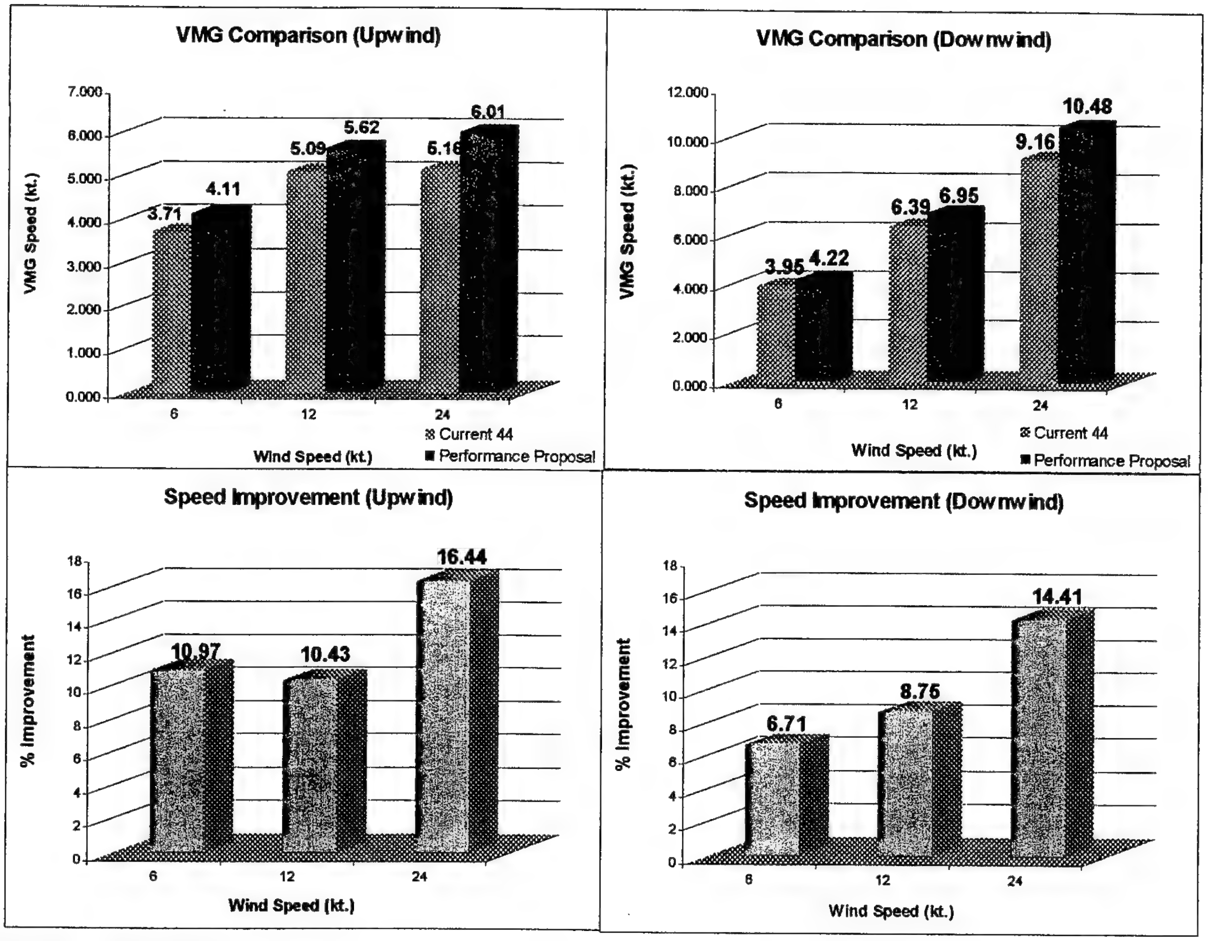
A final suggestion for changes: No effort has yet been made to modify the rudder. A study laid on for the summer has not begun as yet, but changes to the rudder should cause changes in displacement, wetted surface area, and hydrodynamic properties. Likely, an improved rudder will further reduce resistance, and help improve the boat's pointing ability.

## CONCLUSIONS:

VPP data confirms the theory that increased waterline length, decreased displacement, and change in hull shape and appendages increases boat speed. In addition, these changes reduce resistance, allowing for smaller powering requirements while motoring. Of the changes, waterline length proved the most dramatic for speed. For stability, the CG shift of the keel provided the most assistance. The following bar graphs depict the VMG speeds of the mid-line proposal compared to the current boat. Note the percent change in speeds upwind and downwind. **(Fig. 1-4 mid-line)**




Similar but more dramatic values were
achieved with the performance proposal. Graphed data clearly indicates that the proposed new hull forms cause dramatic improvements in performance. Simply put, a few

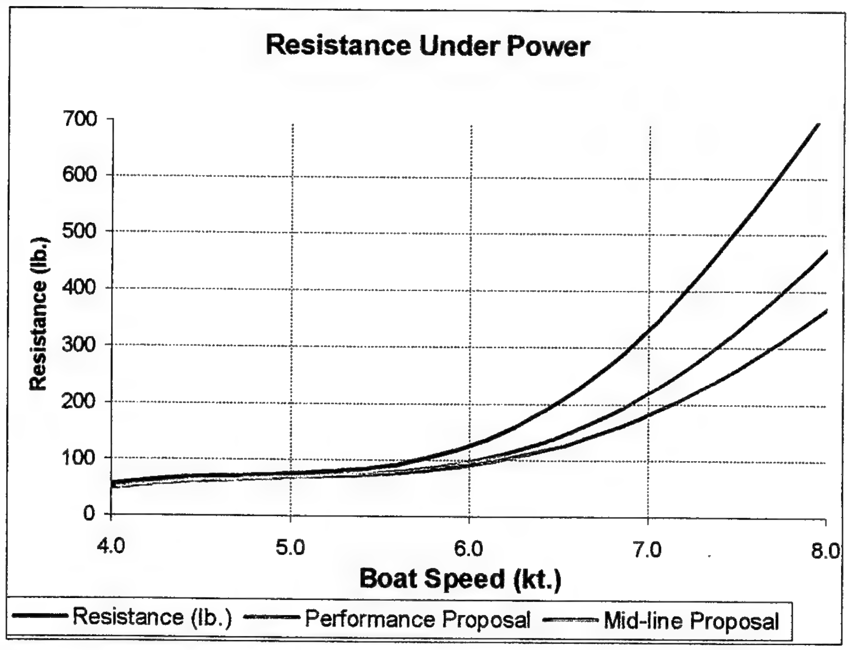



**(Fig. 5-8 performance)**

relatively minor changes to the current design allow for a faster, more stable boat. More research data is attached to this report. Polar plots of boat speed comparisons for both the mid-line and performance proposals are included in the annex.

In a practical sense, these suggestions translate to three important benefits to Navy sailing. First, the higher speed ensures quicker transit times. This will improve scheduling difficulties for CSNTS and VOST cruises and ensure greater safety for midshipmen. Second, the faster sailing speeds of the boats will ensure more actual time under sail. This increases the training aspect of summer cruises in the sailing program.

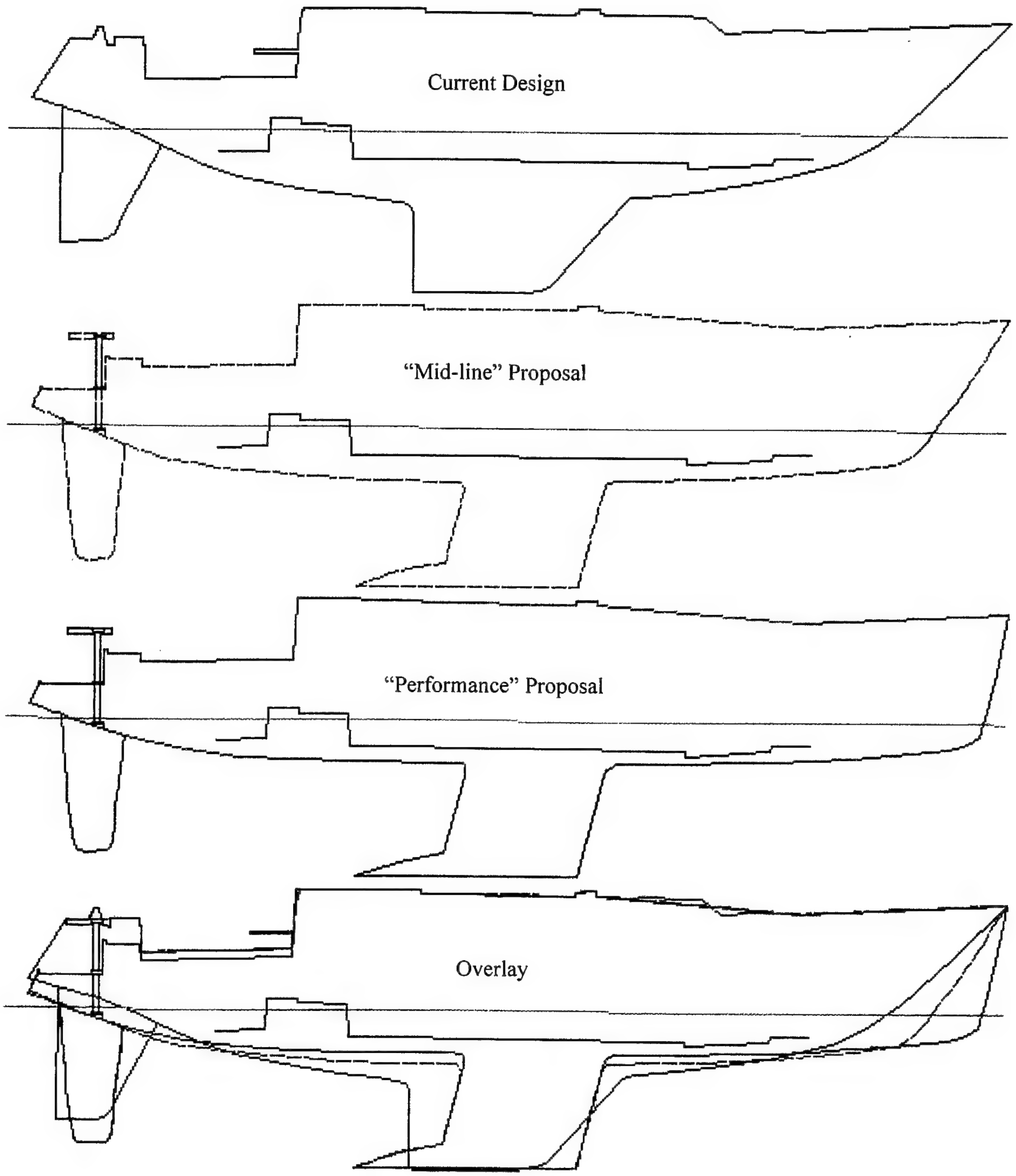
Finally, as the resistance graph above shows, reduced resistance at cruising




**(Fig. 9 Resistance Curve)**

speeds translates to lower wear on engines, smoother motoring, and lower fuel bills, all of which benefit the overall program. According to VPP data, at about 6.2 knots boat speed (a reasonable cruising speed for the current design), the current boat generates about 150 pounds of resistance. At the same resistance, the mid-line proposal could produce as much as a quarter to half knot improvement in motoring boat speed, while the performance proposal could generate even more.

## Navy-44 Design & Proposals:




The above centerline profiles of hulls and appendages represent the suggested design modifications as tested in the VPP. The two proposed designs also comply with the new keel concept and the suggested modifications to the deck layout. The line present in the center of each drawing above represents the location of the current design's cabin sole.

<u>**Navy 44 Hull Laminate Weight Reduction Analysis**</u>

MIDN 1/C Mark H. Arvidson
Prof. P. H. Miller, Advisor
August 2000

## 1.0 Introduction

The goal of the Navy 44 Laminate Weight Reduction Analysis was to determine the best resin, core, and laminate stacking sequence to be used in the construction of the new Navy 44 sloops. The product of the spring independent research project was a target weight reduction of one thousand pounds for the Navy 44's hull and deck laminates. That target weight reduction could theoretically be attained, while increasing the toughness and stiffness of the laminate, by using a symmetric laminate with three layers of eighteen-ounce biaxial cloth on either side of three quarters of an inch thick, six-pound per cubic foot, foam core with an epoxy resin system. The Laminator, a computer program using classical laminated plate theory, predicted that this laminate would have equal or greater strength than the current laminate. A laminate test matrix, Table 1, was created to find the best resin, core, and laminate stacking sequence. All the laminates were symmetrical except as indicated in the "Plies" column, where colons separate the outer skin from the inner skin layup. All the laminated panels were made by Bill Beaver in the TSD Model Shop at the United States Naval Academy using donated materials.

| Laminate | Plies | Core | Resin |
|---|---|---|---|
| C0 | 1.5/2x2410:2x2410 | Airex | Corezyn 8117 |
| C1 | 3x18: | Airex | Proset 125 |
| C2 | 3x18: | Divinycell | Proset 125 |
| C3 | 3x18: | Corecell | Proset 125 |
| C4 | 3x18: | WestCore | Proset 126 |
| L1 | 18/24/18: | Airex | Proset 125 |
| L2 | 18/24(45°)/18: | Airex | Proset 125 |
| L3 | 4x24:3x24 | Airex | Proset 125 |
| L4 | 18/K/18/18: | Airex | Proset 125 |
| R1 | 3x18: | Airex | Proset 117 |
| R2 | 3x18: | Airex | MAS |
| R3 | 3x18: | Airex | USC 2000 |
| R4 | .75/3x18:3x18 | Airex | Corezyn 8117 |
| R5 | .75/3x18:3x18 | Airex | Derakane 8084 |
| R7 | 3x18: | Airex | USC 4200 |

Table 1.0 – Laminate Test Matrix

From the standpoint of manufacturing the Navy 44's of different laminates, there are several advantages and disadvantages to using one resin system over another. During the production of the laminated panels, only one of the vinyl ester resin systems, Derakane 8084, did not attack the Airex core. Another problem with the materials was that some

laminates were resin-starved as a result of wicking of the surface layer into the fabric. The MAS epoxy seemed most likely to do this wicking or soaking into the core. The easiest manufacturing method seemed to be by resin-infusing the panels, as opposed to hand lay-up. Taking each of the manufacturing pros and cons into consideration, if the boats were made with a vinyl-ester resin system, Derakane 8084 would be the best choice, and if the boats were made with an epoxy resin system, Proset 125 would be best.

## 2.0 Four-Point Flex Test

The first experiment done to determine the best laminate was the Four-Point Flex Test performed with the SATEC machine. In the flex test, a one-inch wide by sixteen-inch long fiberglass coupon was placed on support rollers that were fourteen inches apart with the tensile, or inside, skin down, as seen in Fig. 2.0. A two thousand pound load cell with rollers spaced nine inches apart was then lowered on the compressive, or outside, skin.

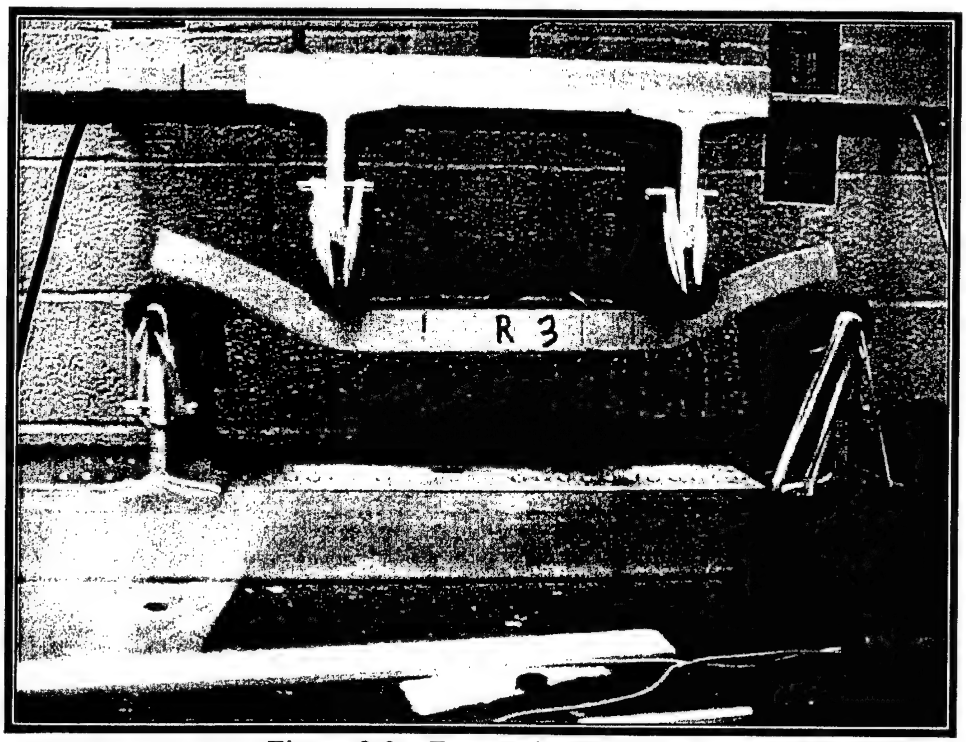



Figure 2.0 – Four-Point Flex Test

As the position of the load cell traveled downward, the load cell sent load data and the SATEC machine sent position data to the computer. From the position and load data of five to nine samples per laminate, a curve correlating the load to position was plotted. Figures 2.1 and 2.2 show typical curves representing different failure modes.

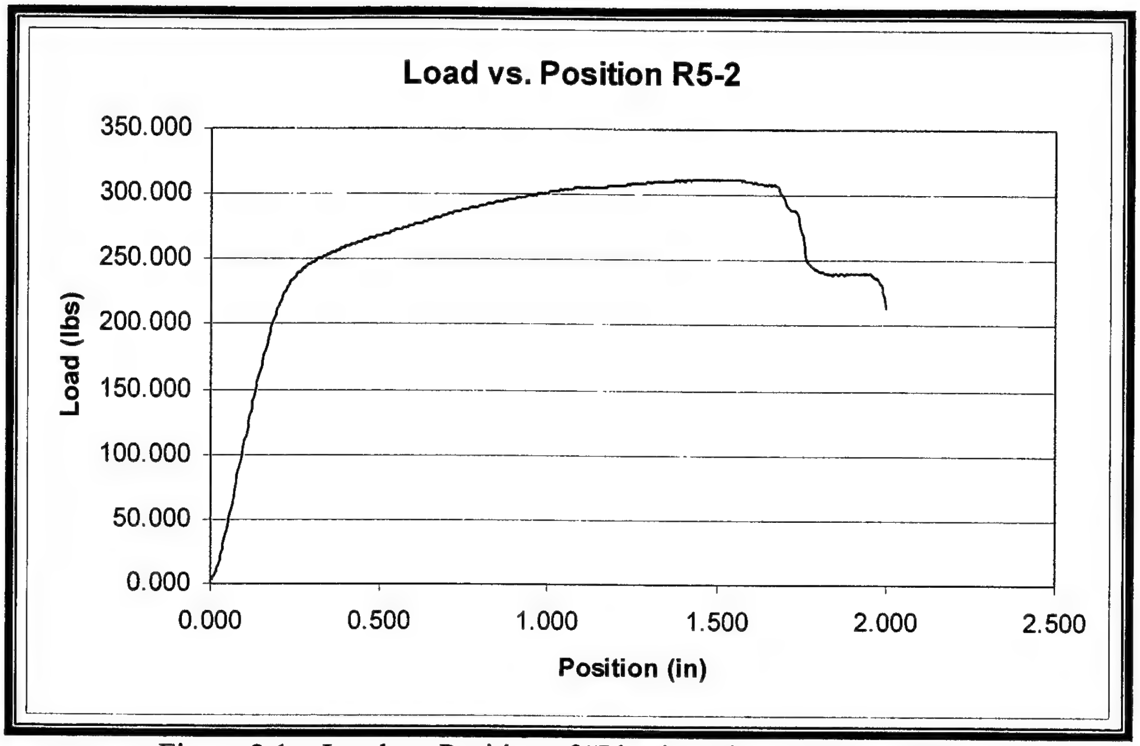



Figure 2.1 – Load vs. Position of "Plastic" Vinyl-Ester Laminate

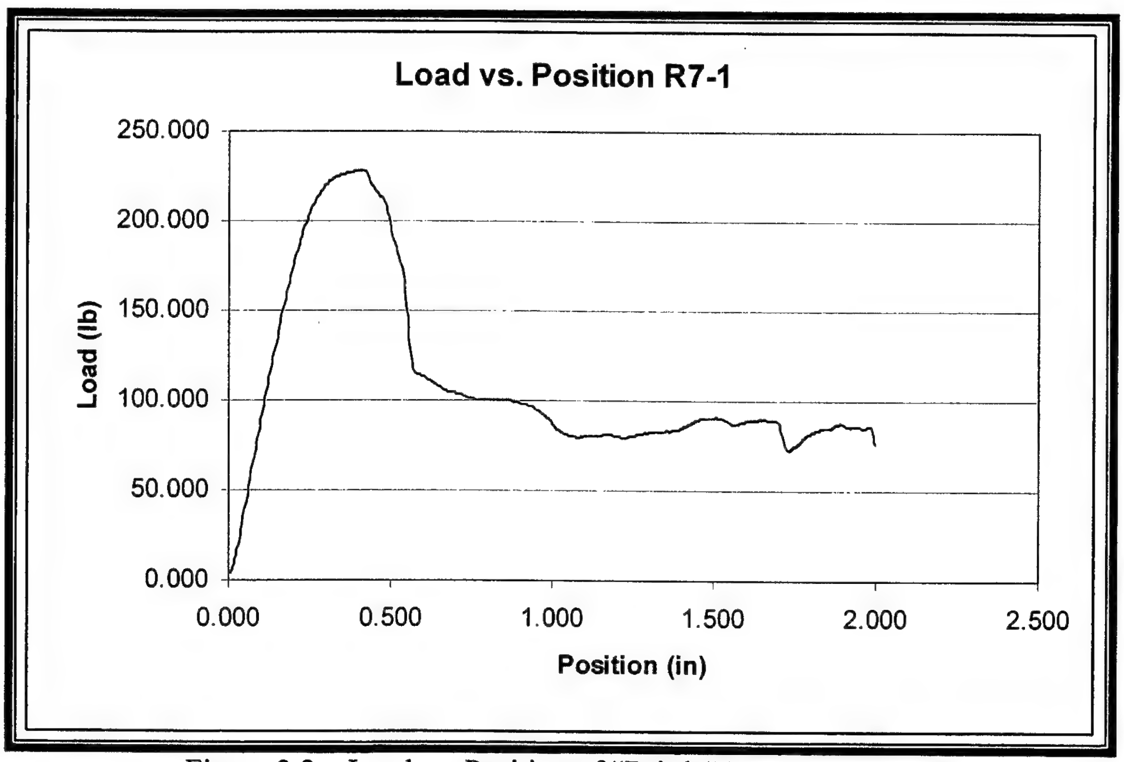



Figure 2.2 – Load vs. Position of "Brittle" Epoxy Laminate

The yield strength per weight of each laminate was then calculated and plotted on a graph, normalized to the yield to weight ratio of the current Navy 44 laminate, C0, as shown in Fig. 2.3.

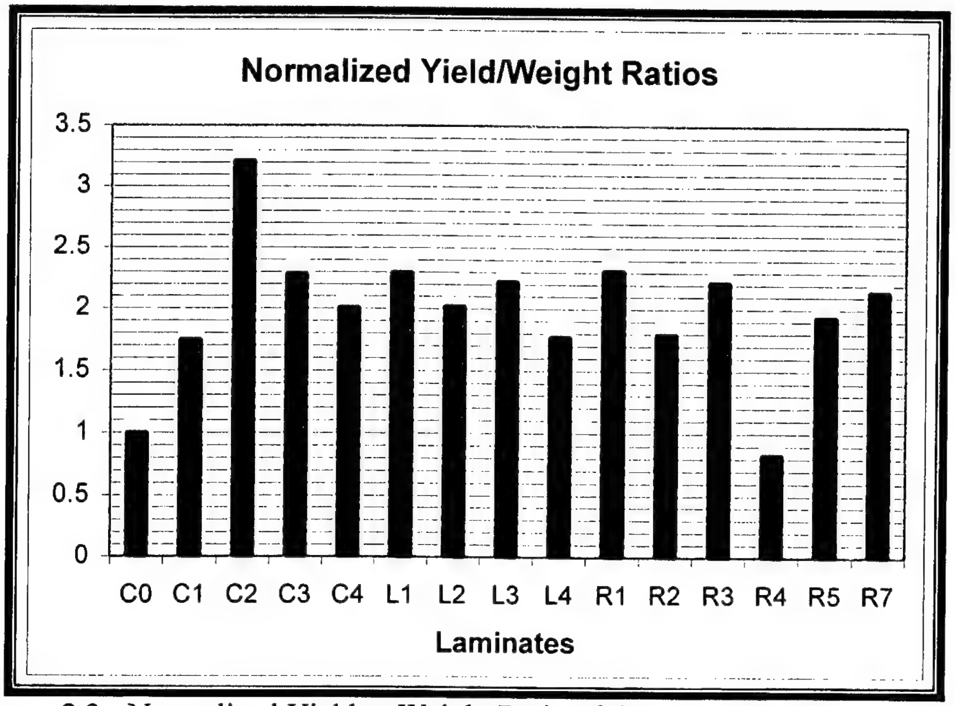



Figure 2.3 - Normalized Yield to Weight Ratio of the Four-Point Flex Analysis

### 2.1 Flex Test Results

Figure 2.3 shows that the Divinycell core, panel C2, significantly outperformed the other cores in bending. Also, the USC and Proset epoxy resin and Derakane vinyl-ester resin laminates; R3 and R7, R1 and C1, and R5 respectively; had almost twice the yield strength per weight of the Corezyn vinyl-ester resin laminates, C0 and R4. Adding one or more layers of twenty-four ounce cloth to replace the eighteen-ounce cloth increased the bending strength of the laminate, as seen with laminates L1 and L3. Adding a layer of Kevlar, as in L4, did not greatly affect the bending strength of the laminate. After the completion of this step in the redesign analysis, it was predicted that the best laminate would be a symmetric laminate with two eighteen-ounce and one twenty-four ounce biaxial cloth plies, the Divinycell core, and the USC 2000 epoxy resin system. The 18/24/18 laminate and Divinycell core would give the greatest yield strength, and the USC resin would allow for a greater reduction in laminate weight while retaining sufficient yield strength.

## 3.0 Print-Through and Weight Analysis

The next analysis was to determine whether or not the resin systems would have any significant print-through of the fiber mesh onto the painted surface due to the heating of the resin by the sun. Due to the wicking of the resin away from the outer plys, most of the panels had to have significant amounts of filler applied to the outer surface before

being painted. This filler addition would need to be added to the initial cost of each laminate as well as the added weight of the laminate. The laminates that required the least painting preparation were the vinyl-ester resin laminates, (which were built with a three-quarter ounce veil mat on the outer surface), and the laminate that required the most preparation was the MAS epoxy, due to the severe wicking of the R2 laminated panel. All the panels were painted by the Naval Station Small Craft Repair Division to a glossy finish, set out in the hazy Maryland sun at approximately ten degrees from vertical, and monitored every hour during the middle of the day with an average ambient temperature of 90 degrees Fahrenheit. Significant surface temperatures ranged from a low of 138 degrees Fahrenheit on L4 to a high of 158 degrees Fahrenheit on R5. Though the average surface temperatures were over ten degrees above the post-cure temperature of all the epoxy resins (140 degrees Fahrenheit), no significant print-through was seen on an any of the panels.

### 3.1 Panel Weights

The finished panels all weighed significantly less than the control panel, C0. The control panel weighed eleven pounds. Even the heaviest panels, the two vinyl-ester panels, R4 and R5, and the asymmetrical panel, L3, would yield a weight savings of over 400 pounds in the total deck and hull laminate for the boat. The greatest weight savings would be to use the USC 2000 resin system as in the R3 panel, with up to 1000 pounds saved.

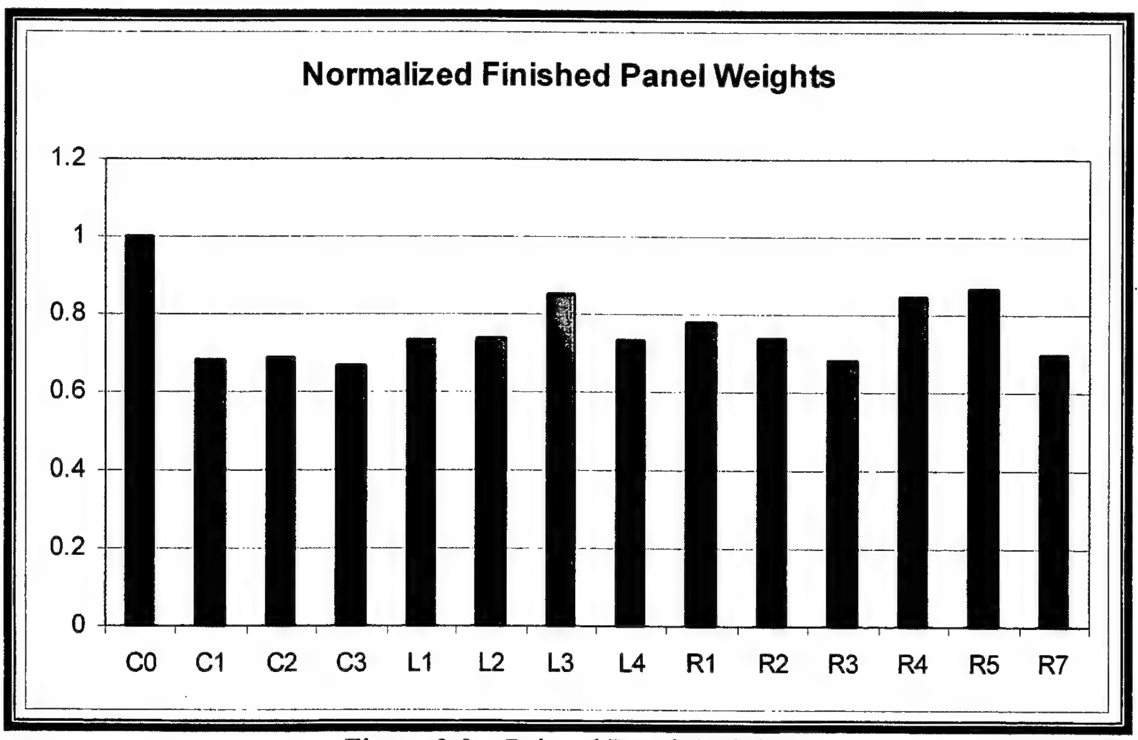



Figure 3.0 – Painted Panel Weights

## 4.0 Panel Pressure Deflection Analysis

Once the panels were painted, a test was conducted to determine the amount each laminate deflected under pressure applied to the panel's outer layer. The two-by-two foot panels were placed on a rubber water-pressure bag. An aluminum frame was placed on the panel so that it held it one half inch on each edge, and two steel beams were placed on the aluminum frame to hold everything down to the base. Water filled the pressure bag until fifteen pounds per square inch pressure was exerted onto the panel. The deflections were measured using string-pots at the center of the panel and on the frame (to subtract the frame deflection from the panel). The pressure was measured at the hose leading to the water-pressure bag.

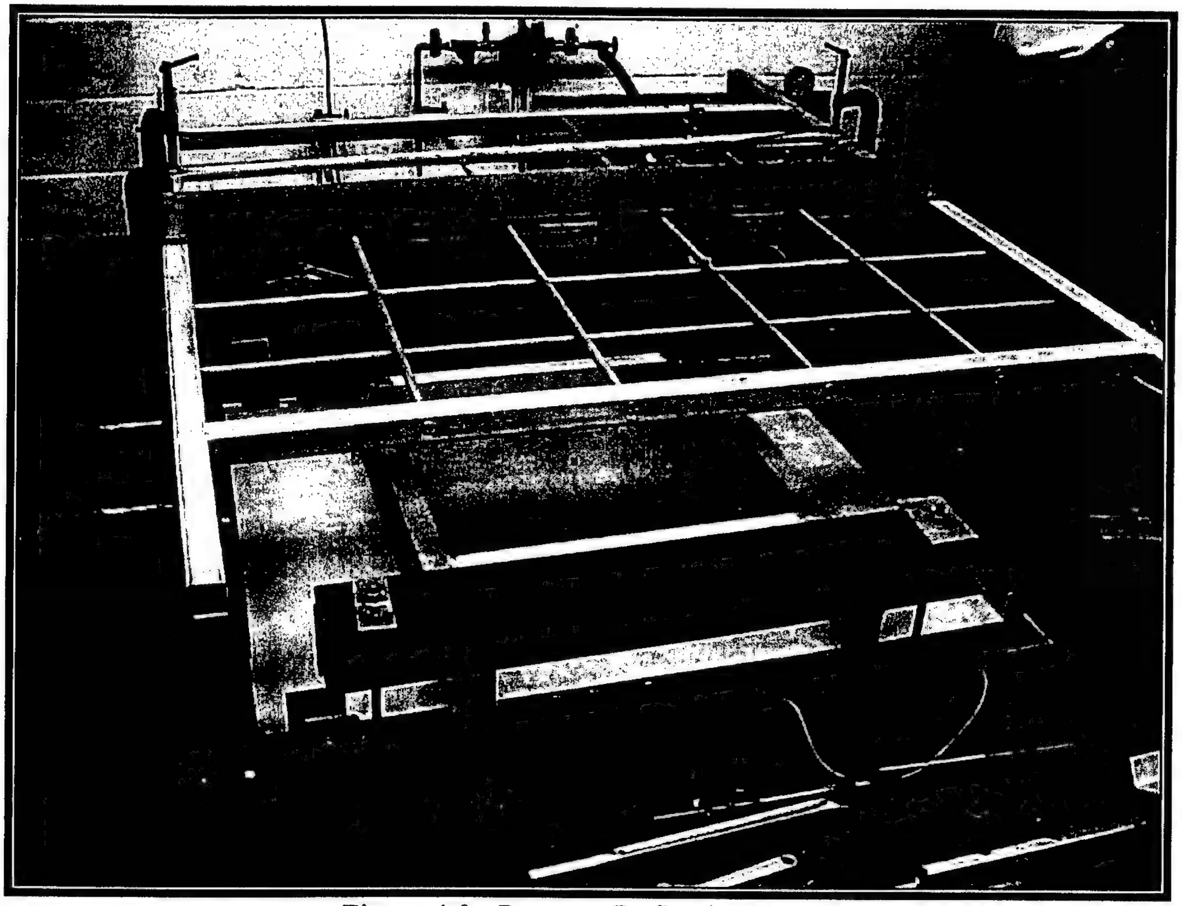


Figure 4.0 - Pressure Deflection Test

### 4.1 Pressure Deflection Results

Results from the pressure analysis show that the laminate L3 had over a third less deflection than the control laminate, C0, under the same distributed load, and less than half the deflection of the R7 panel. The R5 panel, a vinyl-ester panel had almost twenty percent less deflection as compared to the control panel. Especially when dealing with

the less-elastic epoxy resins, having a laminate that deflects less is an advantage, and can be combined with the results of the flex analysis to see that the compressive skin does not buckle.

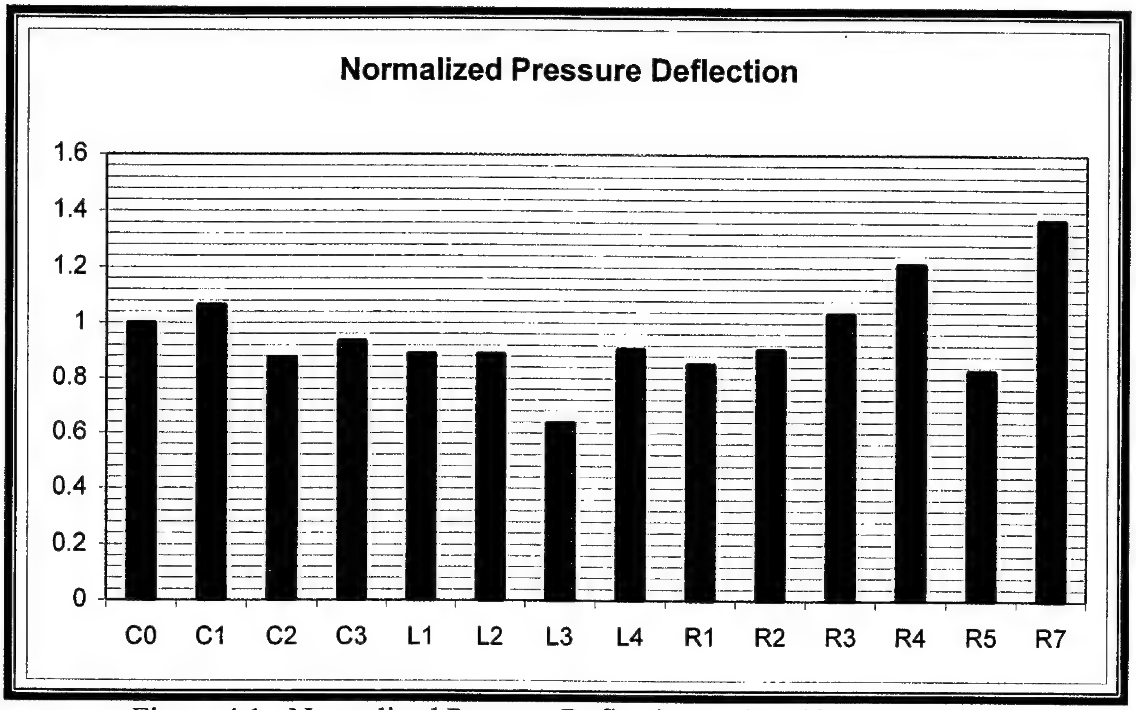



Figure 4.1 - Normalized Pressure Deflection under Fifteen PSI Load

## 5.0 Impact Test

The final laminate analysis was conducted by impact testing the two-by-two foot panels. Before impact testing could begin, a suitable impact machine had to be designed. Keeping in mind that a using the full size and weight of a Navy 44 was not feasible, a replica of the first eight inches of the current Navy 44 sloop's bow was fabricated. George Burton of the TSD Metal Shop made the simulated bow of quarter-inch steel and attached it to two, six-foot long, one and one-half inch steel angles. A one inch by one and one-half inch steel bar was welded to the impact head and angles to connect the two and provide a means of attaching weights to the back of the impact head. The bow impact head, plus added weights, were swung from a bracket that was attached to a large beam assembly. The device dropped from a height of two feet ten inches. Total weight of the impact head, arms, and weights totaled 306 pounds. Figure 5.0 shows the set-up before the whole assembly was moved to a larger frame with better footing and a better pivot bracket.

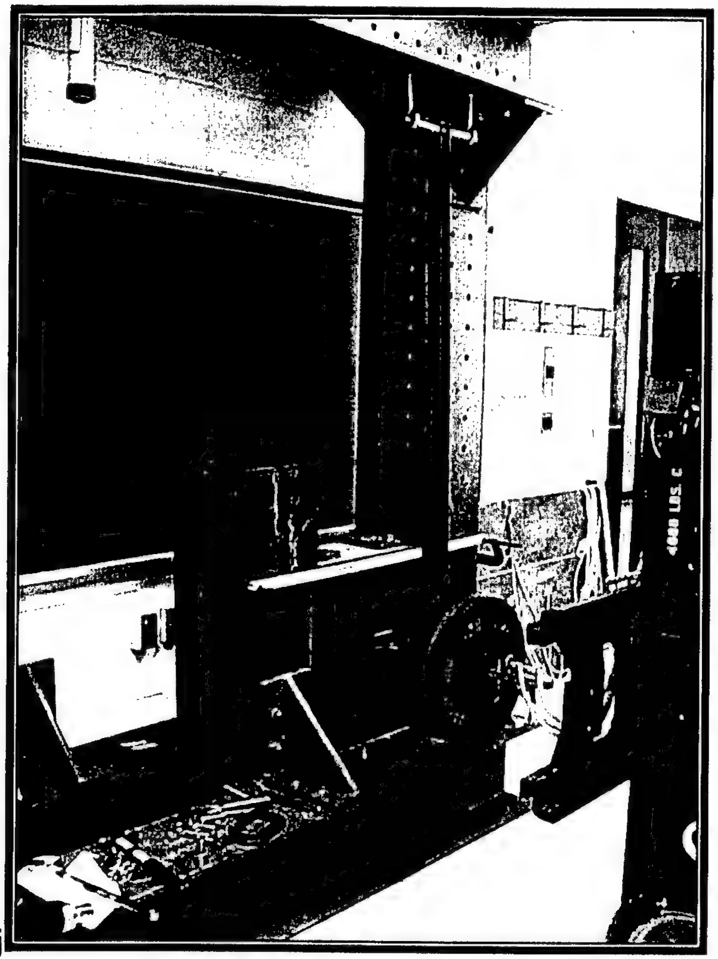


Figure 5.0 - Bow Impact Test Set-up

The height that the weight would be swung from was determined by setting the boat speed at eight and one-half knots. With the correct geometry of impact head and correct velocity of impact, relative impact damage could be determined of each panel as compared to the current Navy 44 laminate. The weight added to the impact head was determined by impacting panels that were not in the analysis and a weight that would produce significant damage to the surface of the average panel if not break it completely. Impacts were video taped and the extent of damage to the laminated panels was determined by visual inspection of the surfaces and by saw cuts through the impact area.

| Laminate | Impact damage | Plastic Def (in) |
|---|---|---|
| C0 | Local punch-through of compressive skin | 0.25 |
| C1 | Local punch-through of compressive skin, local core damage | 0.125 |
| C2 | Local core damage, buckling of compressive skin(vertical), delamination of compressive skin(along buckle line), minor punch-through of compressive skin | 0.25 |
| C3 | Local punch-through of compressive skin, local core damage | 0.125 |
| C4 | Severe core shear failure, delamination of compressive and tensile skins, tearing of both skins, local punch-through of compressive skin | N/A |
| L1 | Local punch-through of compressive skin | 0 |
| L2 | Local punch-through of compressive skin, unseen delamination of compressive side skin 2 inches wide in vertical direction | slight |
| L3 | Core squished slightly, minor scratches on surface | 0 |
| L4 | Local punch-through of compressive skin, local core damage | 0 |
| R1 | Local punch-through of compressive skin, local core damage | slight |
| R2 | Moderate to severe punch-through of compressive skin, local core Damage | 0.25 |
| R3 | Local punch-through of compressive skin, buckling of compressive skin(horizontal and vertical) in lines radiating from impact area, 1/2 inch delamination of compressive skin in buckling area | 0.375 |
| R4 | Local punch-through of compressive skin | 0.125 |
| R5 | Local punch-through of compressive skin | 0.25 |
| R7 | Major buckling of compressive skin(horizontal and vertical) in lines radiating away from impact area, line tear on tensile skin from edge in horizontal direction, 1 inch delamination in area of buckling Lines | 0.25 |

Figure 5.1 - Impact Damage

Repair cost estimates based on average damage repair time estimates, in man-hours, were made by Jim Mumper, planner in the Hull Division, SCRD. An average cost of fifty-five dollars per man-hour was used in this analysis, and the man-hour estimates were modified slightly to include core and delamination damage found once the damaged panels were cut apart.

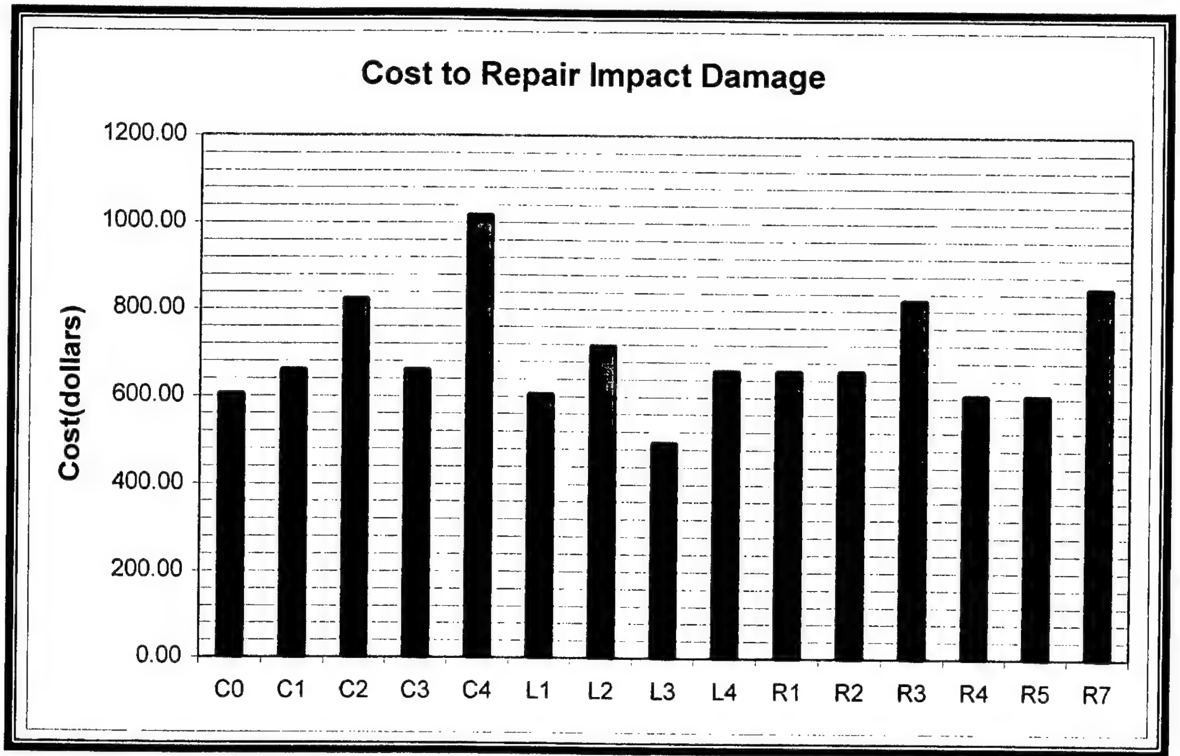



Figure 5.1 - Cost to Repair Impact Damage to Laminates

**5.1 Impact Test Results**

Results of the impact test analysis emphasize some of the strengths of laminates seen in the previous tests and contrast others that were thought to be strengths. Both of the USC epoxy resin system panels, R3 and R7, buckled, the WestCore panel, C4, completely delaminated, and the unsymmetrical laminate that employed twenty-four ounce cloth instead of eighteen-ounce cloth, L3, survived the impact almost unscathed.

## 6.0 Final Results and Recommendations

Laminate L3 experienced the least amount of deflection under pressure or impact. This lack of deflection may have attributed to the fact that the L3 panel did not buckle like R7 or R3 in the impact test. By far, the L3 laminate, which employed a heavier weight biaxial cloth on each side of the core, was the superior impact resistant laminate. From this analysis, it can be concluded that a major factor in the impact resistance of a laminate is the number of layers and weight of biaxial cloth in the compression, or outside, skin. As was seen in the control, C0, the thickness of the outside layer does not have a great affect on impact resistance when the added thickness is from mat. Most of the epoxy resin laminates seemed to have greater impact resistance than the vinyl-ester resin laminates, yet this could change if a heavier weight cloth was used in construction.

### 6.1 Recommendations

1) The strongest epoxy laminate would be three layers of 24 oz biaxial cloth on each side of 6 lb ATC Core-Cell core with the Proset 117 infusion epoxy resin system. The three layers of 24-ounce cloth would provide substantially greater impact resistance than the current laminate and would be slightly lighter.

2) Corecell was the best core because it was easier to form in construction than Airex, and did not have any problems with delamination in the impact test.

3) WestCore performed significantly worse than the other cores.

4) Proset 117 was the best epoxy resin system as it had less deflection under pressure than the Proset 125 epoxy resin system and had the highest yield-to-weight ratio in the flex test. The Proset 117 resin panel, R1, would produce a weight savings of over six hundred and seventy-five pounds for the boat.

5) Derakane 8084 was the best vinyl-ester resin system tested. The Derakane resin panel, R5, would produce a weight savings of over four hundred pounds for the boat. The best vinyl ester did not perform as well as the best epoxy.

6) To attain the greatest weight savings while slightly improving the impact resistance, Laminate L1, with two layers of 18 oz and one 24 oz. on each side, could be used. The total weight savings would be over 800 pounds and the flexural strength would be improved.

**New Navy 44 Deck and Cockpit Layout Concept**
**Interim Report**

MIDN 1/C Cecily Taylor

18 August 2000

Beginning on 1 AUG 00, this internship explored the design process of the Navy 44. Data was collected over the past year from both CSNTS and VOST, along with the opinions and suggestions of numerous knowledgeable people. A variety of boats were surveyed for ideas. This data was collected and then processed into one design for the new Navy 44 deck layout. The first requirement was to meet the ORC and IMS safety standards set for the boat. The next standard was to evaluate each proposed design change to make sure it was safe. Finally, adjustments were allowed to make the boat both a comfortable and effective training vessel as well as an effective racer.

First, the original deck outline had to be converted into CAD. This required learning the system and applying the techniques taught during the school year. Once the old layout was in, it could be altered to reflect the changes in the new design. Research was put into every piece of deck hardware to find the best and most effective replacement system for this deck. The changes had to be calculated into the design so that the deck was still functional. This took most of the time. One design that I used as an example was the J/44. It is functional as a cruiser and as a racer.

The final layout was produced in AutoCad LT along with the plans of the old deck layout. This project will be continued into the academic year as part of a design project. This first drawing is just a preliminary drawing to work off of in the future.

## Changes to the Navy 44

1. **Cleats**: The present cleats on the bow and stern would be changed to "pull-up flush cleats". Presently, lines get snagged in the cleats while underway. Also, midshipmen have been known to injure themselves on the present cleats. These new types of cleats recess flush to the deck when they are not in use. Attwood manufactures this type of cleat.

2. **Forward Large Hatch**: This hatch now opens so that the hatch cover rests on the deck housing. In order to do this the hatch was moved forward so that it is clear of the hatch by the mast. The deck housing has been faired to the hatch edge. This allows the hatch to lie flat on the housing.

3. **Toe Rail**: The toe rail will extend from the bow cleats to the mast. At that point a T-track will be installed in the middle section of the boat with the toe rail beginning again at the primary winch and running all the way aft.

4. **Anchor**: In an effort to make the anchor easily accessible, the anchor will now be housed in a watertight compartment on the deck near the port spreader. The anchor can be secured within the compartment. This will make the anchor more convenient. Also, this will eliminate the chance of the anchor being dropped below after use causing damage to either persons or sails.

5. **Ventilation**: The ventilation has been removed forward of the mast. VOST and CSTS have discovered that the best way to ventilate the boats is by opening the forward hatches with wind scoops while underway. In storms the ventilation is often turned to the back of the boat in an effort to slow the water leakage into the racks; thus, they become less effective. Ventilation has been added to the starboard side of the companionway.

6. **Winches and Rope Clutches**: One winch has been removed on the starboard side. Primarily, Navy sets the jib and spinnaker using the port side. The starboard side is used more as an alternate for a spin peel or a mishap. The spin should remain on a winch since in the event of a broach; the time wasted to apply the pressure to get the rope clutch to release is slower than just blowing the halyard off a winch.

7. **Companionway**: The entrance to the companionway has been recessed back into the cabin housing in an attempt to stop the shower of water that flows into the coach's rack.

8. **Winches**: The primary winch has been moved forward since the traveler has moved. The secondary winch has also moved forward.

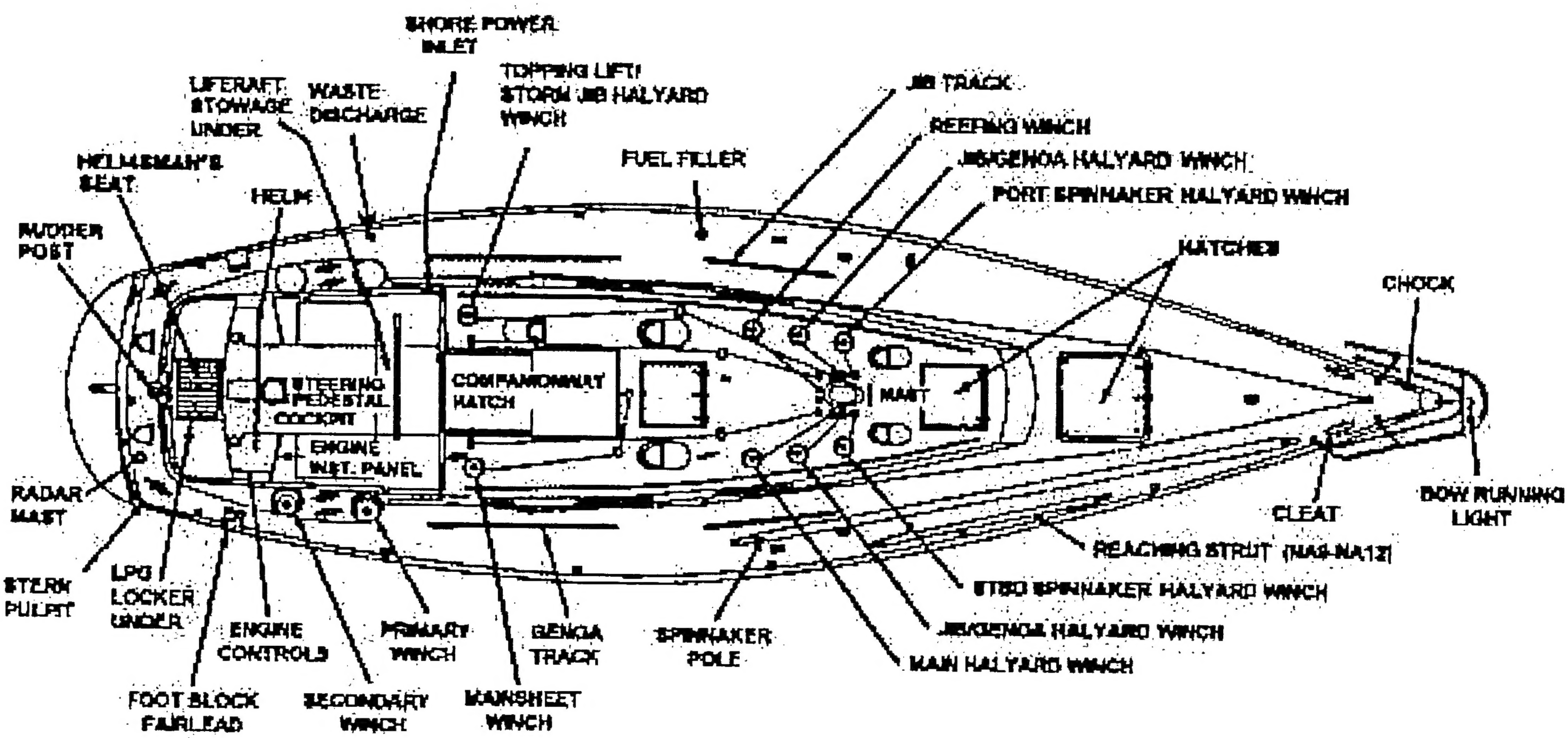
9. **Main Sheet and Traveler**: The traveler has been moved aft and placed in front of the wheel. The main sheet will now have two winches and move to a 4:1 system.

10. **Helm and stern**: The **helm** has also moved back and increased in dimension. The present wheel is slightly small if the driver is trying to see the telltales on the jib. Also, the stern of the boat has been slightly widened to that the driver may also have more visibility when sitting on the side for sailing. There are a number of binnacles that are designed small and round enough that the main sheet would have a hard time catching on them. With a large amount of research, the best steering system for the new set-up would be the Whitlock King Cobra rack and pinion steering system. It has a minimum maintenance record and is built for the rudder torque of a Navy 44.

11. **Cockpit and Seats**: In the new design, the seats are more narrow and longer while the cockpit floor is shallower. Since the cockpit is wider with the increased width of the stern, there is more room in the pit for midshipmen on CSTS or a competitive VOST crew. Foot chocks have been added in the center for a more comfortable ride while the boat is heeled over.

12. **Semi-open stern**: The stern will be open with a step down in the back. The cockpit coming will continue around the stern as a seat for the helm. It will arch over the back in a smooth continuous curve. Under the helm seat, the deck floor will drop below the cockpit floor. At this point the life raft will be secured in the stern and blocks will be added to prevent the life raft from freely falling out of the stern. The life raft will not be secured in place with screws. The blocks will act as a guard to keep the life raft from shifting. This will make the life raft more accessible in times of emergencies. With the open back, a ladder that flips up can be placed to make man-overboards easier to recover. Also, drainage in the cockpit will be better with this open back.

# Old Navy 44


SHORE POWER INLET
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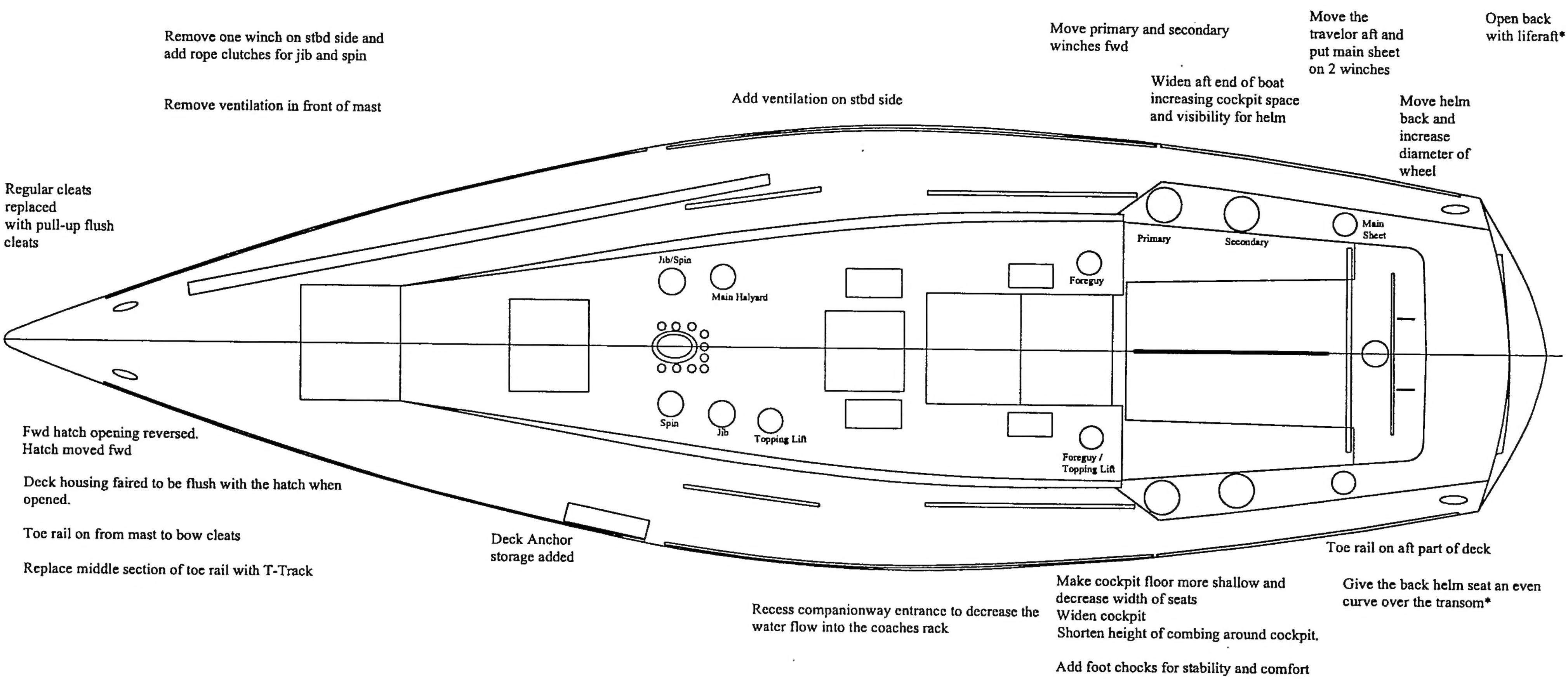
BOW RUNNING LIGHT
CLEAT
REACHING STRUT (NA9-NA12)
STBD SPINNAKER HALYARD WINCH
JIB/GENOA HALYARD WINCH
MAIN HALYARD WINCH
STERN PULPIT
LPG LOCKER UNDER
ENGINE CONTROLS
PRIMARY WINCH
GENOA TRACK
SPINNAKER POLE
FOOT BLOCK FAIRLEAD
SECONDARY WINCH
MAINSHEET WINCH

# Preliminary New Navy 44 Deck and Cockpit Layout




(see ENS DeMeyer's proposed profiles for cockpit elevation view)

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